ผลของการเปลี่ยนแปลงการใช้ที่ดินต่อแหล่งสะสมคาร์บอน กรณีศึกษาพื้นที่ลุ่มน้ำย่อยน้ำยาว จังหวัดน่าน ประเทศไทย

นางปรัชวนี พิบำรุง

วิทยานิพนธ์นี้เป็นส่วนหนึ่งของการศึกษาตามหลักสูตรปริญญาวิทยาศาสตรดุษฎีบัณฑิต
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EFFECTS OF LAND-USE CHANGES ON CARBON STOCKS:
A CASE STUDY IN NAM YAO SUB-WATERSHED,
NAN PROVINCE, THAILAND

Mrs. Prachwanee Pibumrung

A Dissertation Submitted in Partial Fulfillment of the Requirements
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นางปรัชวนี พิบำรุง: ผลของการเปลี่ยนแปลงการใช้ที่ดินต่อแหล่งสะสมคาร์บอน กรณีศึกษาพื้นที่ลุ่มน้ำย่อยน้ำยาว จังหวัดน่าน ประเทศไทย (EFFECTS OF LAND-USE CHANGES ON CARBON STOCKS: A CASE STUDY IN NAM YAO SUB-WATERSHED, NAN PROVINCE, THAILAND) อาจารย์ที่ปรึกษา: รองศาสตราจารย์ ดร.นันทนา คชเสนี อาจารย์ที่ปรึกษาร่วม: รองศาสตราจารย์ ดร. อภิศักดิ์ โพธิ์ปั้น จำนวนหน้า 168 หน้า.

การศึกษาครั้งนี้มีวัตถุประสงค์เพื่อวิเคราะห์ศักยภาพการสะสมคาร์บอนในที่ดินป่าไม้ ป่าปลูก และพื้นที่เกษตรกรรม ในพื้นที่ลุ่มน้ำย่อยน้ำยาว (19°05'10"N, 100°37'02"E) จังหวัดน่าน ประเทศไทย ด้วยวิธีการประเมินจากมวลชีวภาพเหนือพื้นดิน เศษซากพืช มวลชีวภาพใต้พื้นดิน และอินทรีย์คาร์บอนในดินถึงระดับความลึก 1 เมตร ผลการศึกษาพบว่า การสะสมธาตุคาร์บอนแตกต่างกันในที่ดินแต่ละประเภท โดยพื้นที่ป่ามีศักยภาพการสะสมคาร์บอนสูงกว่าพื้นที่ป่าปลูก และพื้นที่เกษตรกรรมอย่างมีนัยสำคัญ ($P < 0.05$) ในพื้นที่ป่าไม้ ป่าดิบเขามีปริมาณการสะสมคาร์บอนรวมสูงสุด (398.43 ± 25.16 เมกกะกรัมคาร์บอนต่อเฮกแตร์) โดยมีการสะสมคาร์บอนในมวลชีวภาพเหนือพื้นดิน เศษซากพืช มวลชีวภาพใต้พื้นดิน และอินทรีย์คาร์บอนในดินตามลำดับดังนี้ 150.07 ± 12.58, 6.86 ± 0.58, 19.56 ± 0.20 และ 221.94 ± 1.66 เมกกะกรัมคาร์บอนต่อเฮกแตร์ ในพื้นที่ป่าปลูก ป่าปลูกที่มีอายุมาก (26 ปี) มีปริมาณการสะสมคาร์บอนรวมสูงสุด (205.67 ± 10.33 เมกกะกรัมคาร์บอนต่อเฮกแตร์) โดยมีการสะสมคาร์บอนในมวลชีวภาพเหนือพื้นดิน เศษซากพืช มวลชีวภาพใต้พื้นดิน และอินทรีย์คาร์บอนในดิน ตามลำดับดังนี้ 40.70 ± 6.36, 2.22 ± 0.13, 11.14 ± 0.18 และ 151.61 ± 3.66 เมกกะกรัมคาร์บอนต่อเฮกแตร์ ในพื้นที่เกษตรกรรม พื้นที่ทิ้งร้าง (6 ปี) มีปริมาณการสะสมคาร์บอนรวมสูงสุด (120.21 ± 2.43 เมกกะกรัมคาร์บอนต่อเฮกแตร์) โดยมีการสะสมคาร์บอนในมวลชีวภาพเหนือพื้นดิน เศษซากพืช มวลชีวภาพใต้พื้นดิน และอินทรีย์คาร์บอนในดิน ตามลำดับดังนี้ 5.91 ± 1.21, 0.15 ± 0.01, 1.01 ± 0.07 และ 113.14 ± 2.26 เมกกะกรัมคาร์บอนต่อเฮกแตร์ การเปรียบเทียบความสัมพันธ์ของแหล่งสะสมคาร์บอนพบว่า ดินมีศักยภาพเป็นแหล่งเก็บกักคาร์บอนสูงสุดในทุกรูปแบบการใช้ที่ดิน รองลงมาคือมวลชีวภาพเหนือพื้นดิน มวลชีวภาพใต้พื้นดิน และเศษซากพืชตามลำดับ การเปรียบเทียบภายในของสัดส่วนเฉลี่ยระหว่างปริมาณคาร์บอนเหนือพื้นดินรวมต่อปริมาณคาร์บอนใต้พื้นดินรวมต่อปริมาณอินทรีย์คาร์บอน ในพื้นที่ป่าไม้ พื้นที่ป่าปลูก และพื้นที่เกษตร มีค่าเท่ากับ 7:1:12, 3:1:14 และ 6:1:106 การศึกษานี้พบว่า การเปลี่ยนแปลงการใช้ที่ดินหรือการจัดการที่ดิน มีผลต่อการสูญเสียคาร์บอนในแหล่งสะสมต่างๆ โดยเฉพาะปริมาณคาร์บอนที่สะสมในมวลชีวภาพเหนือพื้นดินและในดิน โดยมวลชีวภาพเหนือพื้นดินเป็นแหล่งสะสมคาร์บอนที่มีความอ่อนไหวต่อการเปลี่ยนแปลงสูงสุด ในขณะที่คาร์บอนในดินเป็นแหล่งสะสมคาร์บอนที่มีความทนทานต่อการเปลี่ยนแปลงสูงสุด จากการศึกษาทั้งหมดนี้ชี้ให้เห็นว่าการอนุรักษ์และฟื้นฟูระบบนิเวศป่าไม้ และการปลูกป่าสามารถเพิ่มปริมาณการสะสมคาร์บอนในแหล่งสะสมต่างๆ ได้อย่างมีนัยสำคัญ มีผลต่อการลดปริมาณคาร์บอนไดออกไซด์ในบรรยากาศและช่วยลดปัญหาสภาพภูมิอากาศเปลี่ยนแปลง

สาขาวิชา **วิทยาศาสตร์ชีวภาพ** ลายมือชื่อนิสิต ....
ปีการศึกษา 2550 ลายมือชื่ออาจารย์ที่ปรึกษา ....

##4673816523 : MAJOR BIOLOGICAL SCIENCES
KEY WORDS: CARBON STOCKS / ABOVEGROUND CARBON / BELOWGROUND CARBON / SOIL ORGANIC CARBON / NAN PROVINCE

PRACHWANEE PIBUMRUNG: (EFFECTS OF LAND-USE CHANGES ON CARBON STOCKS: A CASE STUDY IN NAM YAO SUB-WATERSHED, NAN PROVINCE, THAILAND. THESIS ADVISOR: **ASSOC. PROF. NANTANA GAJASENI, Ph.D.** THESIS CO-ADVISOR: **ASSOC. PROF. APISAK POPAN, Ph.D.** 168 pp.

The study was conducted to assess carbon (C) stock potential in forest, reforestation and agricultural land-use types and reliably estimate the impact of land use on C stocks in Nam Yao sub-watershed (19°05'10"N, 100°37'02"E), Nan province, Thailand. The carbon stocks of aboveground, litter, belowground, and soil organic carbon within forest, reforestation and agricultural land were estimated through field data collection. Results revealed that total carbon stock of forests was significantly greater than the reforestation and the agricultural land ($P < 0.05$). In the forest, total carbon stock of hill evergreen forest was the greatest (398.43 ± 25.16 Mg C ha^{-1}), followed by aboveground carbon, litter carbon, belowground carbon, and soil organic carbon as of 150.07 ± 12.58, 6.86 ± 0.58, 19.56 ± 0.20 and 221.94 ± 1.66 Mg C ha^{-1}, respectively. In the reforestation, total carbon stock of the 26-year-old reforestation was the greatest (205.67 ± 10.33 Mg C ha^{-1}), followed by aboveground carbon, litter carbon, belowground carbon, and soil organic carbon as of 40.70 ± 6.36, 2.22 ± 0.13, 11.14 ± 0.18 and 151.61 ± 3.66 Mg C ha^{-1}, respectively. In agricultural land, total carbon stock of the 6-year-old fallow land was the greatest (120.21 ± 2.43 Mg C ha^{-1}), followed by aboveground carbon, litter carbon, belowground carbon, and soil organic carbon as of 5.91 ± 1.21, 0.15 ± 0.01, 1.01 ± 0.07 and 113.14 ± 2.26 Mg C ha^{-1}, respectively. Internal comparison of the average total aboveground carbon : total belowground carbon : soil organic carbon ratios (TAGC : TBGC : SOC), was 7:1:12, 3:1:14 and 6:1:106 for the forest, the reforestation and the agricultural land, respectively. This study found that land-use changes and/or land management practices resulted in carbon stocks losses, especially, aboveground carbon and soil carbon. The aboveground carbon pool is highly responsive to land-use changes while the soil organic carbon is more resistant than other pools. Results indicated that significant carbon stocks can occur in forest ecosystem conservation, restoration and reforestation. It is important for decreasing carbon dioxide in the atmosphere and climate change.

Field of study **Biological Sciences** Student's signature....................................

Academic year **2007** Advisor's signature....................................

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I also sincerely thank to all members of Tropical Ecology Laboratory who have spent a great time altogether. Finally, I would like to express all of my love to my mother, father, sisters, brother and my husband who always embrace and encourage me to learn, live and love.

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ACRONYMS

TCS	Total carbon stock
TAGC	Total aboveground carbon
TBGC	Total belowground carbon
SOC	Soil organic carbon
RC	Root carbon
LC	Litter carbon
FRC	Fine root carbon
CRC	Coarse root carbon
TLC	Total litter carbon
Mg	Megagram = tonne
Mg C	Megagram carbon = tonne carbon

CHAPTER I

INTRODUCTION

1.1 OVERVIEWS OF THE STUDY

Deforestation and other land-cover changes typically release carbon from the terrestrial biosphere to the atmosphere as carbon dioxide (CO_2), while recovering vegetation in abandoned agricultural or logged land removes CO_2 from the atmosphere and sequesters it in vegetation biomass and soil carbon. Estimates of carbon stocks in tropical ecosystems are the most important for understanding the global C cycle, the systematization and evaluation of global initiatives to reduce global warming, and the management of ecosystems for carbon sequestration purpose. This information is also useful to estimate the amount of carbon that is potentially discharged to the atmosphere due to land-use changes as well as from natural or human activities. Although forests dominate the terrestrial biospheric carbon cycle due to their large pools and fluxes. Secondary forests, developing from the reforestation or plantation on disturbed or degraded land are also an important component of land cover area in the tropics. In Thailand, the rate of deforestation is so high then secondary forests are an important fragment of total forested area and their distribution is highly heterogeneous, mixed with plantation, croplands, grassland, and primary forests.

Land use change in Thailand has been characterized by rapid alteration of landscapes shaped by human activities for centuries. The change has been particularly significant over the last two decades due to rapid population and economic growth. Under the rapid population growth, the people need more land for their settlement and producing subsistent food which poverty becomes a significant factor influencing forest encroachment in order to convert forest areas to agriculture lands. Therefore, it is obvious that forest degradation is one of major factor contributing greenhouse gas emissions in Thailand, except from the fossil fuel combustion. It occurred largely in the northern part of Thailand where not only highland but also lowland landscapes had been altered by intensive farming and industrialization. This has important implications to Thailand’s carbon budget for two reasons. First, the north is

Thailand’s main source of forest as main carbon stock and watersheds also provide the water supply to lowland especially the central region. Second, the ecosystems in northern Thailand represent some of the most fragile ecosystem types in the nation. The possible change in those ecosystems could strongly disturb the current carbon cycling, influence the functioning of the terrestrial ecosystems in Thailand and, over time, reshape their structural and geographical patterns. These structural changes could in turn affect the climate because of biospheric feedbacks in response to changes in carbon, water and heat regimes. The types and degree of likely ecosystem responses are not well understood but they will likely vary with the biome (forest, grasslands, agroecosystems, wetlands, etc.).

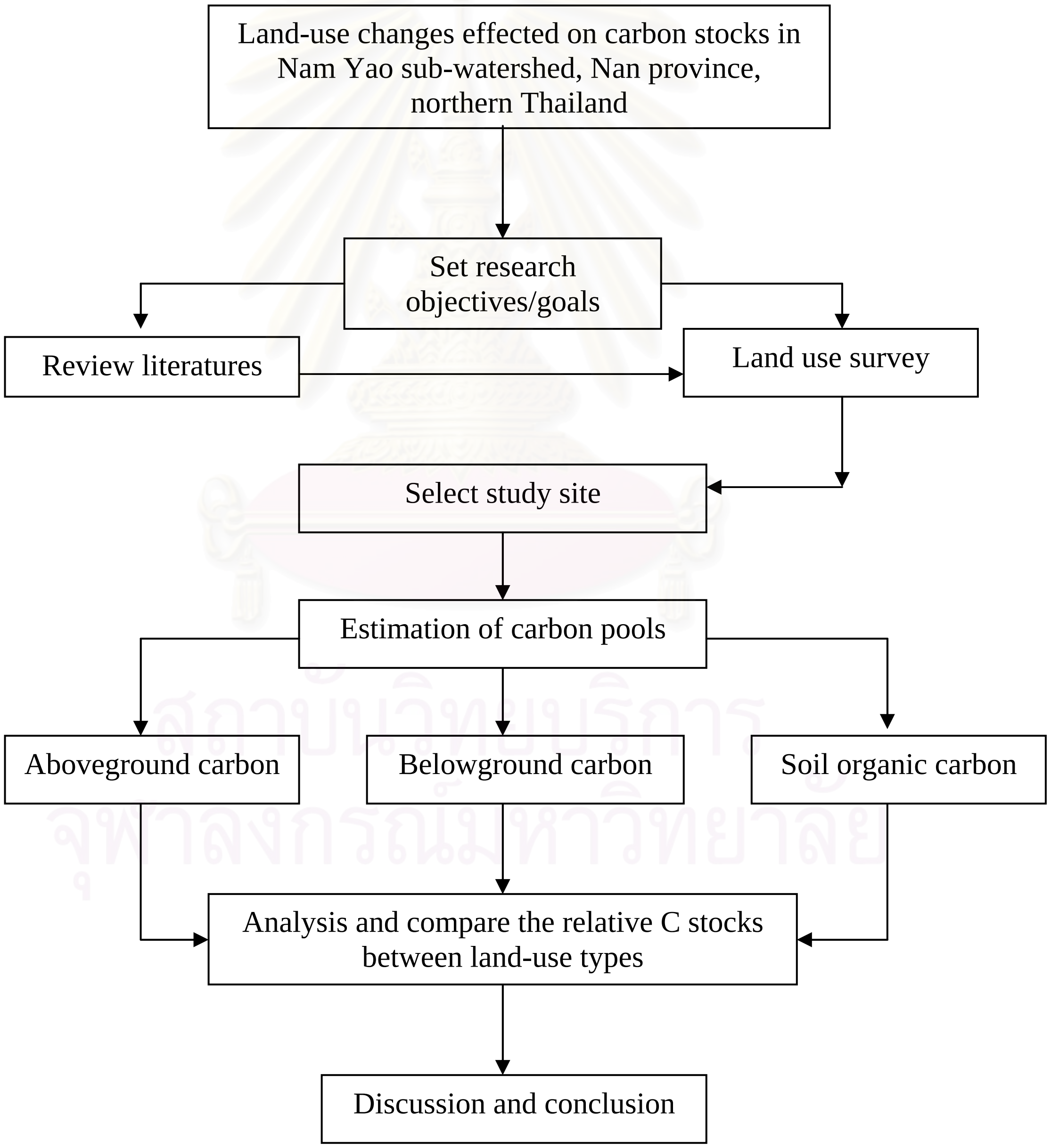
The United Nations Framework Convention on Climate Change (UNFCCC) encourages member countries to plant trees as one of strategy to help meet their carbon dioxide emissions reduction targets. This is one of the mechanisms of the Kyoto Protocol, which is controversial over its capability to solve climate change problem. Although the Kyoto Protocol is primarily imposed to only developed and industrialized countries, but in fact, reducing carbon dioxide is the most crucial mission for every country to save the destiny of our planet earth. This has led to a renewed interest in land-use changes and their implications in the policy, scientific, and business communities. Through the Clean Development Mechanisms (CDM), some countries may reduce net emissions in excess of their legal requirements – these could be sold to other countries that need additional emissions reductions. In many cases, for example, the cost of reducing emissions is cheaper in developing countries than it is in the energy sector of developed countries. Forestry sector, therefore, will be financially attractive for investors from the developed countries to purchase carbon credits from the developing countries to meet obligations agreed to in Kyoto Protocol.

The questions are, do we have institutions strong enough to support the mechanism? How do the carbon stocks estimate and report in the standard of the global information? Therefore, it is necessary for estimating carbon stocks and their distribution in different ecosystem pools, which is important to understand the carbon sequestration potential in various pools of terrestrial ecosystem.

1.2 SCOPE OF THE STUDY

This research establishes a prototype to estimate the carbon stocks in aboveground carbon (live biomass and litter) and belowground carbon (roots and soil organic carbon) in Nam Yao sub-watershed, Nan province, northern Thailand. Besides the study of carbon stock, I am also interested on the ratios between carbon pools between aboveground and belowground carbon stock, these ratios can be persued to estimate the proportion of C stored in different pools.

The scope of the study is designed to estimate various carbon pools as follows:



1.3 OBJECTIVES

The objectives of this study are: (i) to assess carbon stock in various forms in different land-use types; and (ii) to estimate the relative amounts of carbon stocks between carbon pools for use in climate change mitigation.

1.4 ORGANIZATION OF THIS DISSERTATION

The thesis will be organized into six chapters in which Chapter Three, Four and Five will be elaborated in the format of specific topic and readily designed for the academic publication. Therefore, it comprises as follows:

- ***Chapter one*** is an introduction providing an overview of the study, a scope of the study, objectives and an organization of this thesis.
- ***Chapter two*** describes the literature reviews from various sources that are supportive to the study especially in relation to the previous studies in tropical region. Moreover, the reviews are also classified regarding the theme of this study such as aboveground biomass, belowground biomass, soil organic carbon even the carbon stocks in the different land-use types.
- ***Chapter three*** describes the relationships of aboveground carbon and plant community which study on the species composition of plants. The aboveground carbon stocks will include carbon in tree, sapling, seeding, other vegetation as well as in dead biomass e.g. litter and woody debris in different land-use types.
- ***Chapter four*** describes the study of estimations of belowground carbon especially in coarse and fine root, and soil organic carbon in different land-use types. Moreover, this chapter aims to estimate the potential of carbon sequestration between belowground carbon and soil organic carbon, it will be useful for carbon dioxide mitigation management.
- ***Chapter five*** describes the carbon stock in different land-use types which intends to summarize all forms of carbon stock in natural forests, reforestations and agricultural land. This chapter also analyzes the ratios of total aboveground carbon and total belowground carbon within the land-use types.

- ***Chapter six*** describes the summary and recommendation that might be the appropriate strategy for carbon dioxide mitigation reduction by applying the concept of carbon sink in terrestrial systems.

CHAPTER II

LITERATURE REVIEWS

2.1 Carbon and global climate changes

In 2001 the Intergovernmental Panel on Climate Change (IPCC) concluded that most of the warming observed over the last half of the twentieth century can be attributed to human activities that have increased greenhouse gas concentrations in the atmosphere. They also notified that these changes will continue to drive rapid climate changes for next several centuries. Principle amongst these greenhouse gases is carbon dioxide (CO_2), whose atmospheric concentrations have been dramatically altered by human perturbations to the global carbon (C) cycle. Human perturbations to the carbon cycle have been both direct and indirect effects. Obviously the direct effects are the addition of new carbon to the active global carbon cycle through the combustion of fossil fuels, and the modification of the vegetation structure and distribution through land-use change. Deforestation has the largest land-use change impacts on the carbon cycle, both through the loss of photosynthetic efficiency in forest vegetation and the contemporary release of carbon stocks accumulated in forest ecosystems over long periods of time. Indirect human impacts on the carbon cycle include changes in other major global biogeochemical cycles, alteration of the atmospheric composition through the additions of pollutants as well as CO_2, and changes in the biodiversity of landscapes and living species (IPCC, 2001).

Carbon is one of the most significant elements in global cycle. The material composition of plants and animals are approximately 50 percent carbon (by dry weight). Carbon in the form of carbon dioxide (CO_2) and methane (CH_4) is also a significant contributor to greenhouse gases that trap the solar radiation as it is stored and released as long wave emissions from the earth's surface. During the past decade, the average concentration of CO_2 has been increasing by about 1.5 ppm yr^{-1}; as of 2002 the concentration was approximately 365 Gt C, corresponding to about 765 Gt C (IPCC, 2001). Expected greenhouse gas emissions make it virtually certain that atmospheric CO_2 concentrations will exceed 450 ppm. by 2100 (O’Neill and Oppenheimer, 2002).

Carbon represents only 0.27 percent of the elements in the Earth's crust, but because it exists in both reduced and oxidized states, it is vital for life processes (Houghton and Skole, 1993). Carbon is stored in the oceans about 37,400 Gt C (Falkowski *et al*., 2000) and 38,140 Gt C (Sabine *et al*., 2004); in fossil organic carbon about 4,130 Gt C (Falkowski *et al*., 2000) and more than 6,000 Gt C (Sabine *et al*., 2004); in soils about 1,200 Gt C (Falkowski *et al*., 2000) and 3,200 Gt C (Sabine *et al*., 2004); in atmosphere about 720 Gt C (Falkowski *et al*., 2000) and 780 Gt C (Sabine *et al*., 2004); and in land and plants about 650 Gt C (Sabine *et al*., 2004) or plants and animals biomass at 600-1,000 Gt C (Falkowski *et al*., 2000). All forms are linked to the atmosphere. Each storage pools in oceans, soil, and vegetation is considered as a carbon sink because each pool is taking up carbon from the atmosphere. Conversely, each storage pool is also identified as a carbon source for the atmosphere because of the constant exchange or flux between the atmosphere and the pools (Sabine *et al*., 2004). The flux between soil and atmosphere is very large at 60 Pg C per year (Lal *et al*., 1998), because the soil can act as either a source or a sink of carbon.

Terrestrial vegetation stores about 610 Gt C as cellulose in the stems and branches of trees. Soil holds two to three times that much higher in the form of dead organic matter, or humus. Terrestrial vegetation and soil currently absorb about 40% of global carbon dioxide (CO_2) emissions from human activities (Adam, 2001). House *et al*. (2003) reported that terrestrial carbon uptake was in the range of 0.3 to 4.0 Gt C yr^{-1} and 1.6 to 4.8 Gt C yr^{-1} for the 1980s and 1990s, respectively. The terrestrial carbon uptake depends on some combination of several processes: fertilization of plant growth by increased atmospheric CO_2 and by deposition of anthropogenic nitrogen, changes in climatic constraints on vegetation growth, and regrowth of forests in previously harvested areas (Schimel *et al*., 2001). Naturally, the most significant fluxes also occur between the biota/soil layer and the atmosphere (at the rate of 120 Gt yr^{-1} of uptake and release by the biota/soil layer), followed by the ocean surface and atmosphere (at the rate of 100 Gt yr^{-1} in both directions, with a net uptake by oceans of 2.5 Gt yr^{-1}). This natural exchange has been occurring for hundreds of millions of years, but humans are changing this natural rate of exchange through land use, land-use change, and forestry activities (IPCC, 2001). The exchange of carbon between atmosphere and biosphere is an important process in controlling global warming and climate change. The uptake and release of carbon by natural and anthropogenic processes altered ecosystems will also be affected by temperature. According to the latest IPCC scenarios, the average global temperatures will be increased by between 1.4 °C and 5.8 °C by 2100, and by even more at higher latitudes (IPCC, 2000). IPCC (2007) report predicted increase in temperature with more precision at 1.8 °C to 4 °C at the end of the century.

2.1.1 Terrestrial carbon

The dynamics of terrestrial ecosystems depend on interactions between a number of biogeochemical cycles, particularly carbon cycle, nutrient cycles, and hydrological cycle, all of which may be modified by human activities. Terrestrial ecological systems, when carbon is retained in live biomass, decomposing organic matter, and soil, play an important role in the global carbon cycle (IPCC, 2000). Being relatively extensive, carbon dense and highly productive, tropical forests play a pivotal role in the global carbon cycle. To illustrate: the carbon flux in relation to human activities, during year 1750-2000, land-use change released 180 Pg C to the atmosphere and 60 % from the tropics (Houghton, 2003); and 283 Pg C released from fossil fuel over the same time period (Marland *et al.*, 2003). Further major carbon additions are possible, with 553 Pg C residing within remaining tropical forests and soils (IPCC, 2001), and to be equivalent to the use of fossil fuel over 80 years at current rates. Inter-annual variability in the rate of increase in atmospheric CO_2 concentrations can be partially explained by large and rapid changes across the tropical CO_2 fluxes. Since direct measurements of atmospheric CO_2 began in 1957, the lowest rate of increase was 1.9 Pg C yr^{-1} in 1992 and the highest was 6.0 Pg C yr^{-1} in 1998. Statistically, El Niño years have shown the highest rates of increase in atmospheric CO_2 concentrations, apparently largely driven by higher deforestation rates, and increased mortality and decreased growth in intact tropical forests (Langenfelds *et al.*, 2002; Page *et al.*, 2002). Understanding the role of terrestrial tropics as a major source (from deforestation) and sink (from undisturbed forest uptake) of CO_2 is essential. Changes in the size of the different carbon pools represent the aggregated effects of human activities on natural carbon flows (Erb, 2004).

2.1.2 Carbon stocks and carbon estimation

Estimations of carbon stocks in tropical ecosystems are high relevance for understanding the global C cycle, the formulation and evaluation of global initiatives to reduce global warming, and the management of ecosystems for C sequestration purposes. However, detailed knowledge about the absolute and relative distribution of C stocks in tropical forests is still limited (Houghton, 2005). Naturally, terrestrial carbon stocks are sequestered in above and belowground. Estimates of aboveground and belowground biomass provide fundamental information on the size and changes of the terrestrial carbon pools as land use and associated land management practices change. In the tropics, estimates of C stocks using ground-based measurements are usually focused on quantifying the aboveground component (Houghton, 2005), while other carbon pools such as belowground biomass, necromass, and soil carbon are seldom measured. Detailed quantifications of total C stocks in tropical area are scarce, a major cause of uncertainty associates with the assessment of this region’s C balance (Schimel *et al*., 2001; and Houghton, 2005).

Global Forest Resources Assessment (FRA) proposed the variables relating to global assessment of growing stocks, biomass and carbon stocks that were measurable and readily for assessing global forest resources (Marklund and Schoene, 2006). These variables provided the significant pools of carbon stocks that can be considered for carbon estimation of land use. The following variables on biomass and carbon are in the following:

- Growing stock
- Aboveground biomass
- Belowground biomass
- Dead wood
- Carbon in dead wood
- Carbon in aboveground biomass
- Carbon in belowground biomass
- Carbon in litter
- Carbon in soil

The stock change in the forest pools provides an approximation of emissions and removals of carbon dioxide as a result of afforestation, reforestation and deforestation. IPCC (2001) suggested that five pools must be considered in estimating and reporting emissions and removals from forests including aboveground biomass, belowground biomass, litter, dead wood and soil organic carbon. It is clear that this definition of “sink” requires the five forest pools to be considered together. In addition, IPCC (2003) provided supplementary methods and good practice guidance for estimating, measuring, monitoring and reporting on carbon stock changes and greenhouse gas emissions from Land Use, Land-Use Change and Forestry (LULUCF) activities under Article 3, Paragraphs 3 and 4, and Articles 6 and 12 of the Kyoto Protocol. IPCC (2003) defined definitions for terrestrial pools in LULUCF sector in Table 2.1.

Table 2.1 Definitions for carbon terrestrial pools

Living biomass	Aboveground carbon	Carbon in all living biomass above the soil including stem, stump, branches, bark, seeds, and foliage.
	Belowground carbon	Carbon in all living biomass of live roots. All living biomass of live roots. Fine roots of less than (suggested) 2mm diameter are often excluded because these often cannot be distinguished empirically from soil organic matter or litter.
Dead organic matter	Carbon in dead wood	Carbon in all non-living woody biomass not contained in the litter, either standing, lying on the ground, or in the soil. Dead wood includes wood lying on the surface, dead roots, and stumps larger than or equal to 10 cm in diameter or any other diameter used by the country.
	Carbon in litter	Carbon in all non-living biomass with a diameter less than a minimum diameter chosen by the country in various states of decomposition above the mineral or organic soil. This includes the litter, fumic, and humic layers. Live fine roots (of less than the suggested diameter limit for belowground biomass) are included in litter where they cannot be distinguished from it empirically.
Soil	Soil organic carbon	Organic carbon in mineral and organic soils (including peat) to a specified depth chosen by the country and applied consistently through the time series. Live fine roots (of less than the suggested diameter limit for belowground biomass) are included with soil organic matter where they cannot be distinguished from it empirically.

Total forest ecosystem carbon of biomass and dead wood accounted for 44 and 6 percent, respectively, while soil to a depth of 30 cm and litter contribute approximately 46 and 4 percent, respectively (Food and Agriculture Organization of the United Nations [FAO], 2005a). Carbon stocks in forest biomass reached the highest values per hectare in Central and South America and Western and Central Africa, while the carbon stocks in East Asia, North Africa and West and Central Asia were reported the lowest values in Table 2.2 (FAO, 2005a). IPCC (2000) estimated an average carbon stock of 86 tonnes per hectare in the vegetation of the world’s forests for the mid-1990s. The corresponding carbon stocks in biomass and dead wood in forests were reported about 82 tonnes per hectare in 1990 and 81 tonnes per hectare in 2005.

Table 2.2 Carbon stocks (ton per hectare) in biomass, dead wood, litter and soils (30 cm depth) by regions for the year 2005 (FAO, 2005a).

Region/subregion	C in living biomass ($t\ ha^{-1}$)	C in dead wood ($t\ ha^{-1}$)	C in litter ($t\ ha^{-1}$)	C in soil ($t\ ha^{-1}$)	Total C ($t\ ha^{-1}$)
East Asia	37.0	5.0	-	-	41.9
South and Southeast Asia	77.0	9.0	2.7	68.4	157.1
Western and Central Asia	39.70	3.6	11.4	41.0	95.8
Total Asia	57.0	6.9	2.9	66.1	132.9
Eastern and Southern Africa	63.5	7.5	2.1	-	73.0
North Africa	26.0	3.3	2.1	33.5	64.9
Western and Central Africa	155.0	9.8	2.1	56.0	222.9
Total Africa	95.8	7.6	2.1	55.3	160.8
Total Europe	43.9	14.0	6.1	112.9	176.9
Carribbean	99.7	8.8	2.2	70.5	181.2
Central America	119.4	14.4	2.1	43.2	179.2
North America	57.8	8.8	15.4	35.8	117.8
Total North and Central America	60.1	9.0	14.8	36.6	120.6
Total Oceania	55.0	7.4	9.5	101.2	173.1
Total South America	110.0	9.2	4.2	71.1	194.6
World	71.5	9.7	6.3	73.5	161.1

C-sequestration depends on ecosystem in the sum of all carbon pools. Many biomass assessment studies conducted are focused on aboveground forest biomass (Laclau, 2003; and Losi *et al*., 2003) because it accounts for the majority of the total accumulated biomass and carbon in the forest ecosystem. However, belowground production is often greater than aboveground production in perennial, native ecosystems (Coleman, 1976). In forests, coarse roots represent most of the standing root crop, but fine roots account for most belowground production (Steinaker and Wilson 2005). Furthermore, accurate estimate of soil organic carbon (SOC) storage is required to assess the role of soil in the global carbon cycle, particularly the effect of soil on atmospheric composition (Garnett *et al*., 2001).

2.1.2.1 Aboveground carbon (ABGC)

Aboveground biomass is defined as the total amount of aboveground living organic matter in trees and vegetation expressed as oven-dry tonnes per unit area. The biomass of trees includes leaves, twigs, branches, bole, and bark. Biomass is an important parameter to assess the atmospheric carbon that is absorbed or utilized by trees. Recently, biomass-related studies have become significant due to growing awareness of carbon credit system the world over (Kale *et al*., 2004). The importance of biomass, relative to other C pools, will depend on the dominant types of land use, the region and time interval.

In the tropics, biomass is of primary importance, knowing it allows calculation of the amount of C lost through deforestation (Houghton, 2005). Two methods of measuring sample tree biomass are available: (i) destructive and (ii) non-destructive. The conventional destructive method is done by cutting the sample tree and then weighing it. Direct weighing can only be done for small trees, but for larger trees, partitioning is necessary so that the partitions can fit into the weighing scale. In cases where the tree is large, volume of the stem is measured. Sub-samples are collected, and its fresh weight, dry weight, and volume are measured. The dry weight of the tree (biomass) is calculated based from the ratio of fresh weight (or volume) to the dry weight. This procedure requires considerable amount of labour and cost, and the use of ratio is biased (Cochran, 1963). However, destructive methods do not allow the development of individual plants to be followed and they require many individuals to be cultivated for repeated measurements. Non-destructive methods do not have these limitations. For example, a non-destructive method based on digital image analysis which address not only above-ground fresh biomass and oven-dried biomass, but also vertical biomass distribution as well as dry matter content and growth rates (Tackenberg, 2007). Lu (2006) mentioned three approaches to biomass assessment. These are field measurement, remote sensing, and GIS-based approach. The field measurement is considered to be accurate (Lu, 2006) but proves to be very costly and time consuming.

The change in biomass stocks can be assessed either as a difference between the biomass increment and biomass removals or as a change of biomass stocks between consecutive inventories (IPCC, 2003). Due to the high requirements on the resources for measurements, biomass assessment under field conditions in practice is done in either of two indirect ways. The first way is to apply an appropriate biomass equation (BE) that predicts tree biomass as a function of diameter at breast height (DBH), or DBH together with other data of measured sample trees, again practically from forest inventories:

$$B = f\ (P1, P2, \ldots, p1, p2, \ldots) \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Somogyi } et\ al\text{., 2006)}$$

where B is the biomass (fresh or dry plant mass, kg or t)
$P1$, $P2$, etc. is the available tree data (e.g. DBH, cm; height, m)
$p1$, $p2$, etc. is the parameter(s) of the equation.

The other way to estimate biomass is to use the volume data of certain compartments of trees or stands as reported by forest inventories or other national statistics and to multiply it with an appropriate factor or factors, referred to biomass factors (BF) to convert and, if necessary, expand or reduce the available volume estimates to the required biomass estimates:

$$B = P \times BF \ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots\ldots \text{(Somogyi } et\ al\text{., 2006)}$$

where B is the biomass (fresh or dry plant mass, kg or t)
P is an available tree or stand parameter (e.g. tree volume, m^3)
BF is an appropriate biomass factor that may include a conversion and, if necessary, an expansion component.

Note that there are many terms used for these factors in the literature. Probably the most frequently used name is biomass expansion factor (BEF). However, BEF is only one type of biomass factors. A factor to be used to estimate biomass may or may not expand, but it always converts the available tree or stand parameter, unless this parameter is biomass of some sort. The term biomass factor is to be used to refer to any factor that can be used alone or in combination with other factors to estimate biomass from volume, and ‘‘biomass expansion factor’’ is to be used to only refer to factors that expand. This method can be used if only aggregated volume estimates, e.g. volume of growing stock by tree species, are available, whereas biomass equations are preferred if one has access to representative sample of tree-wise data from target population (Somogyi *et al*., 2006).

Estimation of forest biomass is an essential aspect of studies of C stocks and the effects of deforestation and C sequestration on the global C balance, as well as for other purposes. Weighing tree biomass in the field is undoubtedly the most accurate method of estimating aboveground tree biomass, but it is an extremely costly and time consuming and destructive method generally limited to small areas and small sample sizes. A common method for estimating forest biomass is through the use of allometric equations which relate the biomass of individual trees to easily obtainable non-destructive measurements such as diameter or other easily measurable variables. A common form is follow:

$B = aD^b$ ……………………………………… (Ketterings *et al*., 2001)

Where B is biomass

D is diameter

A and b are parameters

This non-destructive method to estimate biomass can achieve accuracies of up to 95% and provides a model for growing plantations in similar ecological conditions (i.e. location, topography, and climate) and within the same range of diameter and height (Redondo-Brenes and Montagnini, 2006).

A protocol for forest biomass assessment based on the use of these allometric relationships will involve four steps: (i) choosing a suitable functional form for the allometric equation; (ii) choosing suitable values for any adjustable parameters in the equation; (iii) field measurement of the input variables such as tree diameter; and (4) using the allometric equation to give the aboveground biomass of individual trees and summation to get area estimates (Ketterings *et al*., 2001).

2.1.2.2 Soil organic carbon (SOC)

Soil organic carbon (SOC) represents one of the major pools in the global C cycle. Therefore, even small changes in SOC stocks cause important CO_2 fluxes between terrestrial ecosystems and the atmosphere (Stevens *et al*., 2006). Soil stores two or three times more carbon than exists in the atmosphere as CO_2 (Davidson *et al*., 2000). Soil organic carbon includes plant, animal and microbial residues in all stages of decomposition. Many organic compounds in the soil are intimately associated with inorganic soil particles. The turnover rate of the different soil organic carbon compounds varies due to the complex interactions between biological, chemical, and physical processes in soil (Post and Kwon, 2000).

However, SOC stock estimates are highly uncertain largely because of data gaps for many regions of the world. SOC stock depends on local climatic and other site-specific conditions, as well as on the type of land use and land management, it is sensitive to human interference, and to changes in land use and soil management (IPCC, 2000). The size of SOC pool and its change are mostly controlled by soil environmental characteristics and vegetation types (Zhen *et al*., 2007). Five main management-related factors set the actual SOC level (i.e., reduce the attainable level). First, loss of soil material though erosion reduces soil C, soil volume and/or clay content. Second, increased oxidation, by e.g., tillage or increased soil temperature due to removing vegetative cover, can rapidly reduce SOC levels. Third, removal of organic residues reduces carbon inputs. Fourth, disruption of the soil biotic processes responsible for the breakdown of organic inputs will reduce the availability of SOC fractions suitable for forming the stable organo-mineral complexes. Fifth, drainage aerates the soil which promotes oxidation of SOC (Ingram and Fernandes, 2001).

Globally, the relative distribution of SOC with depth has stronger association with vegetation than climate, but the opposite is true for the total amount of SOC (Jobbágy and Jackson, 2000). Changes in the dominant plant life form or community type (e.g. grasses, shrubs or trees) greatly influence soil C content, chemistry and distribution, as plant life forms differs in litter chemistry, patterns of detrital input and rooting depth (Gill and Burke, 1999). Moreover, plant functional types significantly affected the vertical distribution of SOC. The proportion of SOC in the top 20 cm (relative to the first meter) was 33%, 42%, and 50% on average for shrublands, grasslands, and forests, respectively (Jobbágy and Jackson, 2000). Similarly, different vertical SOC distribution was found among five biomes in China, the proportion of SOC in the top 20 cm averaged 42%, 48%, 34%, 32%, and 34% for forest, meadow, steppe, desert, and cropland, respectively (Yang *et al*., 2007). In Thailand, Chidthaisong and Lichaikul (2005) found that total soil carbon storage in the 0-50 cm layer was 118, 66, 60 ton C ha^{-1} in natural forest (dry evergreen forest), reforestation (*Acacia mangium*) and agricultural area (maize), respectively. It showed that more than 50% of this soil carbon was stored in the top 0-20 cm. When compared between the 16-year old reforestation soil and a continued agricultural soil, the reforestation soil resulted in an increase in soil carbon about 10 tonne C ha^{-1}.

a) Factors affecting soil organic carbon

Whether soil C increases or decreases with afforestation may be determined by a number of factors, including previous land use (Paul *et al*., 2002), site preparation (Zinn *et al*., 2002), type of species planted (Paul *et al*., 2002; Resh *et al*., 2002), climate (Paul *et al*., 2002; Guo and Gifford, 2002), and soil type (Jackson *et al*., 2002). Nevertheless, chemical and physical properties of soils also influence the level of resistance of soil organic C (SOC) to degradation (Swift 2001). It also finds that parent material, climate and geological history are of major importance to affect soil properties at large spatio-temporal scale. However, topography and land use may be the dominant factors of soil properties at hill slope and small catchment scale (Wang *et al*., 2001).

In addition to climate, vegetation and soil texture also play important roles in sharping the SOC stock patterns, which together explained 25.1% of the variance in SOC. The SOC density of forests (10.5 kg m^{-2}) is higher than that of steppe (6.6 kg m^{-2}) and desert (2.6 kg m^{-2}). High SOC density is found in latosols, latosolic red earths, and yellow earths, which are closely associated with their high clay content (Yang *et al*., 2007).

b) Soil properties affecting vertical SOC distribution

Soil bulk density clearly increased from forest to pasture at all studied depths. Soil bulk density increased with pasture decline in the top soil layer, reflecting the decrease in soil cover by pasture biomass and litter (Müller *et al*., 2004).

Texture is one of the most important characteristic of soil, influencing directly and indirectly a cascade of relations between organic matter, ions, and soil drainage. Moreover, the soil textural is main variable associated with aboveground live biomass (Zarin *et al*., 2001). Clay and silt play an important role in the stabilization of organic compounds and small variations in topsoil texture could have large effects on SOC (Bationo and Buerkert, 2001). The highest SOC concentrations were obtained in the silt and clay, which are important in the longer term due to the complex associations of C with the structure of clays (Jiménez and Lal, 2006). Generally, C content and status in the soil is closely associated with clay and silt contents and clay type, which influences the stabilization of organic carbon. Aggregates physically protect SOC through formation of barriers between microbes and enzymes and their substrates thereby controlling microbial turnover (Six *et al.*, 2002). The lower value of SOC in forestland was, basically, due to the dominant contents of gravel and stone (Upadhyay *et al.*, 2005). However, the low clay content and lack of aggregation (i.e., absence of soil organic matter protection and stabilization) in coarse-textured soils are major factors that limit the soil carbon storage capacity (Sartori *et al.*, 2007).

Globally, the relative distribution of SOC with depth had a slightly stronger association with vegetation than with climate, but the opposite was true for the absolute amount of SOC. Total SOC content increased with precipitation and clay content and decreased with temperature. The importance of these controls switched with depth, climate dominating in shallow layers and clay content dominating in deeper layers, possibly due to increasing percentages of slowly cycling SOC fractions at depth (Jobbágy and Jackson 2000).

Rates of change in soil organic matter and its C content are important for sustaining soil fertility and sequestering (or releasing) C to the atmosphere. Soil C storage is controlled in part by decomposition, which can increase or decrease following N additions to soil and litter (Carreiro *et al.*, 2000; and Neff *et al.*, 2002). Symbiotic biological nitrogen (N) fixation can add high quantities of nitrogen annually to forests. The increase in soil N under N_2 fixers is often concomitant with an increase in soil C (Resh *et a*l., 2002). Progressive nitrogen limitation also holds that ecosystems can initially overcome CO_2 induced N limitations through increased C:N in plants and soils, increased N use efficiency for plants, or a transfer of N from organic pools with low C:N ratio to those with higher C:N ratios (Luo *et al.*, 2004). However, C:N ratios for total soil organic matter and particulate organic matter increased with increasing C. Nitrogen concentrations also decline with depth, but to a lesser extent than C. Consequently, C/N ratios decrease with depth, probably reflecting the loss of C from the more highly decomposed organic matter at depth.

C/N ratios of top and deep soils were wider in most forests compared with the same layers in the corresponding fields (Grünzweig *et al*., 2004).

Most of previous studies on the SOC estimation divided soil profile into several layers to calculate SOC density for each layer, and then summed up these densities to obtain total carbon density for the soil profile (Mendoza- Vega *et al*., 2003; Wu *et al*., 2003; and Grunzweig *et al*., 2004). To estimate the SOC in difference land-use types in this study, the sample collection followed the convention used by many ecosystem scientists (Mendoza- Vega *et al*., 2003; and Grunzweig *et al*., 2004) of focusing on the upper 100 cm of the soil profile.

2.1.2.3 Fine root carbon

Roots are the link between soil and plants. The quality of roots is an important factor in the root utilization by soil biota, and thus in rate of decomposition and associated nutrient cycling. Root litter production thereby feeds back to primary production and is relevant to global C budgets (Zak *et al*., 2000). In forests, coarse roots represent most of the standing root crop, but fine roots account for most belowground production (Steinaker and Wilson, 2005). Fine roots also show great turnover and decomposition rates, which affect nutrient availability in soils (West *et al*., 2004). Fine root turnover is of critical importance when assessing nutrient and carbon fluxes in a plant-soil system, as the fluxes below ground might be higher than those above ground (Andersson and Majdi, 2005). The average C:N:P ratio in living fine roots is 450:11:1, and global fine root carbon is more than 5% of all carbon contained in the atmosphere (Jackson *et al*., 1997). Fine root production has been estimated to account for up to 33% of global annual Net Primary Production, NPP. (Gill and Jackson, 2000). In soil, fine roots make up more than 50% of total carbon found in the upper 10 cm (Silver *et al*., 2005). The roots near the soil surface undergo much rapid changes than the deep roots (Hendrick and Pregitzer, 1992). The vertical distribution of roots response to elevated CO_2 in soil (Arnone *et al*., 2000 cited in Higgins *et al*., 2002). Fine root location in the upper part of the soil profile seems to be influenced by availability of nutrients in the soil (Schmid and Kazda, 2002). The large variation in fine root biomass may partly reflect differences in species composition and/or environmental conditions of the forests studied (Leuschner *et al*., 2007).

The ratio fine roots/leaf biomass increases with the age of the stand, while the relative contribution of the leaves and fine roots to the total biomass decreases. The relative importance of the woody tissues on the other hand increases with stand age (Vanninen *et al*., 1996 cited in Vande Walle *et al*., 2001). In forest ecosystem, there was an increase in fine root biomass with increasing forest age (Giese *et al*., 2003). The potential for CO_2 enhancement of fine root productivity mandates that analysis of ecosystem responses to atmospheric change take a whole-ecosystem approach. Analysis based solely on aboveground production will possibly miss a significant fraction of C and underestimate the potential of the ecosystem for additional C storage (Norby *et al*., 2004).

Fine root net primary production constitutes an important, but often unmeasured, part of the carbon budget of forest ecosystems. Direct measurements are problematic in many ways, and the assessment methods are extremely labour-intensive. Several methods, have been used to measure fine root biomass, production and root turnover; most often by sequential coring (Ahlström *et al*., 1988; Yin et al., 1989; and Helmisaari *et al*., 2002) or ingrowth cores (Makkonen and Helmisaari, 1999; Jones *et al*., 2003), minirhizotron method (Burton *et al*., 2000; and Higgins *et al*., 2002).

The soil coring method is suitable for measuring standing biomass, but has several limitations when used for assessing root turnover and requires assumptions about root growth and mortality that can be difficult to ascertain. Ingrowth cores can be used to get a quick and less labourious estimate of relative fine root production. However, it has four major limitations: (i) it provides no information on the time scale of root-ingrowth or mortality; (ii) many of the in-growing roots are from damaged roots as all the roots in the plane of the core are cut; (iii) nutrient availability and soil structure are altered when soil is placed in the cores; and (iv) as with sequential cores, concurrent growth and mortality during the recolonization interval cannot be measured directly. The use of minirhizotrons in recent years has improved our knowledge of fine root dynamics because they allow the concurrent measurement of fine root production and mortality (Andersson and Majdi, 2005;). Limitation of the minirhizotron technique is that if roots are only classified as dead when they disappear, their longevity will be overestimated (Majdi *et al*., 2005).

In the previous studies a variety of data is found concerning fine root distribution in soil. Fine root proliferation in litter layers is a response to nutrient availability in the litter rather than due to the lack of nutrients in the soil (Sayer *et al*., 2006). Moreover, it may become especially important that the greatest increases in root production in elevated CO_2 occur in deeper soil, where sequestration into longer-lived pools may be more likely. The vertical distribution of the fine roots tends to be more shallow than that of long roots; about 78% of < 1 mm root biomass and 61% of 1-2 mm biomass were found to be located in the forest floor, 10 cm mineral soil horizon (Ostinen *et al*., 2005). Guo *et al*. (2005) reported that soil C changes were positively correlated with live fine root length density in the soil under various species in controlled environments from a 1-year pot study. Guo *et al*. (2007) found that soil carbon and nitrogen stocks to 100 cm under the plantation were significantly less than under the pasture by 20 and 15%, respectively. A 36% greater mass of fine root was found in the soil under the pasture than under the plantation and the length of fine root was about nine times greater in the pasture. The annual inputs of fine root litter to the top 100 cm soil, estimated from soil coring and minirhizotron observations, were 6.3 Mg dry matter ha^{-1} $year^{-1}$ (containing 2.7 Mg C and 38.9 kg N) under the plantation, and 9.7 Mg ha^{-1} $year^{-1}$ (containing 3.6 Mg C and 81.4 kg N) under the pasture. Green *et al*. (2005) studied effects of drought and nutrients on fine root longevity in a rainforest through a combination of soil coring and root window observations. They found that the median longevity of small roots was lower than that of larger roots and water availability was more important than nutrients in controlling fine root biomass and dynamics.

Herbaceous plant roots were located mostly in the upper 30 cm, above a clayey, dense soil layer. Root length density of herbaceous plants decreased exponentially with depth until 100 cm depth. Trees (*Quercus ilex* L.) showed a much lower root length density than herbs, in the first 10 cm of the soil depth (Moreno *et al*., 2005).

2.1.2.4 Litter carbon

The forest floor comprises litter (leave, root, and fine woody material) and partially decomposed organic matter that accumulates above mineral soil in many forest ecosystems. Some forest floors also contain substantial amounts of mineral particles that are mixed from below by animals or other agents. The wide diversity of structures, masses, and compositions of forest floors suggested that they might hold the key to understanding major features of forests, such as productivity and sustainability (Yanai *et al*., 2003). Changes in species composition of forests could cause considerable changes in forest floor masses. Shifts in ranges of tree species have been predicted in response to climate change (Walther *et al*., 2002).

Litterfall and turnover in forest ecosystems show large temporal variations due to environmental factors such as temperature, rainfall and wind. Litter turnover can be manipulated by inoculating different groups of soil fauna and microorganisms to the litter layer. In addition, litter turnover in soils may considerably reduce C sequestration due to limited nitrogen (N) availability (Seneviratne, 2002). Litterfall in forests has been shown to increase as a consequence of elevated CO_2 (Finzi *et al*., 2001; and Zak *et al*., 2003). Increased litter production and the predicted decrease in litter quality may lead to a build-up of fresh organic matter on the soil surface, with consequences for fine root distribution, production and turnover (Norby *et al*., 2001). Increased leaf litter inputs promoted the proliferation of fine roots into the litter layer, resulting in a more superficial fine root distribution and lower overall fine root biomass (Sayer *et al*., 2006). Thus root proliferation in litter layers is a response to nutrient availability in the litter rather than due to the lack of nutrients in the soil. Therefore, litter carbon is considered as one of the most important forest carbon ecosystem processes.

Assessments of the forest floor and carbon content in litter pools often are limited in Thailand. Most of studies collected monthly litterfall for one year as litterfall production and separated into leaves, wood, reproductive and other unidentified components. All litter were assumed to have 50% C content, based on the mean C content of fresh leaves and wood (IPCC, 1996).

2.2 Land use, Land-Use Change and Forestry (LULUCF)

Human activities related to land conversion and agricultural practices have also contributed to the build-up of carbon dioxide to the atmosphere. During the past 150 years, land use and land-use changes were responsible for one-third of all human emissions of CO_2. The dominant drivers of current and past land-use-related emissions of CO_2 are the conversion of forest and grassland to crop and pastureland and the depletion of soil carbon through agricultural and other land-management practices (IPCC, 2000). For instance, land-use changes in the tropics are estimated to contribute about 23% to human-induced CO_2 emissions (Houghton, 2003). The IPCC (2001) estimated a total sequestration potential of between 1.53 and 2.47 Pg C yr^{-1} between 2000 and 2050 globally by agricultural management (33%), tropical regeneration (18%), tropical forestation (15%), slowing deforestation (14%), and tropical agroforestry (6%). However, tropical deforestation is usually associated with the conversion of forest to pasture and agricultural land using fire as a land clearing mechanism (Cairns *et al*.,2000).

Land Use, Land-Use Change and Forestry (LULUCF) is a term often used in climate change topics. Land use, land-use change and forestry all have impacts on the global carbon cycle and as such these activities can add or remove carbon dioxide from the atmosphere, contributing to climate change (IPCC, 2000). Current and past land use practices are critical in determining the distribution and size of global terrestrial carbon (C) sources and sinks (Canadel, 2002). When the vegetation decomposes, they release carbon back to the atmosphere. Disturbances in the forest due to natural and human influences lead to more carbon released into the atmosphere than the amount used by vegetation during photosynthesis (Brown, 2002). The per hectare changes in carbon stocks resulting from changes in forest area (deforestation, reforestation, afforestation) are more easily documented than other changes in carbon stocks. Because of the changes are large; the biomass of forests is 20-50 times greater than the biomass of agricultural lands (Houghton, 2005).

Land use and soil management practices can significantly influence SOC dynamics and C flux from the soil (Post and Kwon, 2000). For example, in the early 1980s, land use changes were estimated to have resulted in the transfer of between 1 and 2 Pg C yr^{-1} from terrestrial ecosystems to the atmosphere. Between 15 and 17%

of this C came from the oxidation of SOC (Houghton *et al.*, 1991). Generally, the potential storage and sequestration capacity for CO_2 in various soils is large. IPCC (2001b) estimated that about 83 to 131 Gt C could be sequestered in forests and agricultural soils by 2050.

Accelerated mineralization following land clearing and continuous cropping has been reported to decrease SOC by up to 30% (Nandwa, 2001). Land use practices involving soil disturbance and removal of crop biomass have been the main causes of land degradation by destroying soil structure and loss of SOC. The loss of SOC also contibutes the build up of CO_2 in the atmosphere (Yang *et al.*, 2003). IPCC (2001) estimated that land-use change (e.g. conversion of forest into agricultural land) contributes a net 1.6 ± 0.8 Gt C yr^{-1} to the atmosphere. Loss of SOC can be reversed by ceasing cultivation and returning to the original land cover or other perennial vegetation Average global C sequestration rates, when changing land use from agriculture to forest or grassland, were estimated to be 33.8 or 33.2 g C m^{-2} yr^{-1}, respectively (Post and Kwon, 2000). Conversion of natural forests to tree plantations and perennial crops reduce C density by at least 50% relative to natural forests (Lasco, 2002).

2.2.1 Forest

The role of forests in carbon sequestration is probably best understood and appears to offer the greatest near-term potential for human management as a sink. Forest biomass accumulates carbon over decades and centuries. Furthermore, carbon accumulation potential in forests is large enough that forests offer the possibility of sequestering significant amounts of additional carbon in relatively short periods. However, forest carbon can also be released quickly when the forest burns (Sedjo, 2006). Forest ecosystems are deems to be an important factor in climate change because they can be both sources and sinks of atmospheric CO_2. They can assimilate CO_2 via photosynthesis and store carbon in biomass and in soil (IPCC, 2000). Therefore, forest ecosystem plays a very important role in the global carbon cycle, it stores about 80% of all above-ground and 40% of all below-ground terrestrial organic carbon (IPCC, 2001). During productive season, CO_2 from the atmosphere is taken up by vegetation and stored as plant biomass (Phat *et al.*, 2004). For this reason, the

United Nations Framework Convention on Climate Change (UNFCCC) and its Kyoto Protocol recognized the role of forests in carbon sequestration. Specifically, Article 3.3 and 3.4 of the Kyoto Protocol pointed out forest as potential carbon storage (Brown, 2002).

FAO (2005) reported that carbon in forest biomass decreased in Africa, Asia and South America in the period 1990-2005, but increased in all other regions. For the world as a whole, carbon stocks in forest biomass decreased by 1.1 Gt of carbon annually, owing to continued deforestation and forest degradation, partly offset by forest expansion (including planting) and an increase in growing stock per hectare in some regions. Total forest area as of 2005 is estimated at 3,952 million hectares or 30 percent of total land area. Distribution of forests of South and Southeast Asia comprise all 283,127,000 ha, about 7.2 percent of global forest area. Change in area of forest by region, the net loss of forests from 2000 to 2005, about 2.8 million hectares per year (FAO, 2005).

Tropical forests play a critical role with respect to global carbon pools and fluxes as these forests store about half of the world's biomass (Brown *et al.*, 1996) and 20% of the global soil carbon (Jobbágy and Jackson 2000). In tropical Asia, it is also estimated that forestation, regeneration and avoided deforestation activities have the potential to sequester 7.50, 3.8-7.7 and 3.3-5.8 Pg C between 1995-2050 (Brown *et al.*, 1996). FAO (2005) also reported that from 1990 to 2005, carbon in biomass decreased in South and Southeast Asia, 33 Gt in 1990, 26 Gt in 2000 and 22 Gt in 2005. IPCC (2000) estimated an average carbon stock of 77.0 t ha^{-1} in the vegetation, 68.4 t ha^{-1} in soil for South and Southeast Asia in the year 2005.

There are limited data on C densities of natural forests in the specific Southeast Asian countries. Recent studies showed that Indonesian forests have been estimated to have a C density ranging from 161-300 Mg C ha^{-1} in aboveground biomass, 150-254 Mg C ha^{-1} in belowground biomass and upper 30 cm of soil and 390 Mg C ha^{-1} in above ground biomass and below ground pools. Philippines natural forests contain 86-201 Mg C ha^{-1} in aboveground biomass. Whist, the IPCC Revised Guidelines estimates that old-growth forests in the Philippines contain 370-520 Mg ha^{-1} of aboveground biomass equivalent to about 185-260 Mg C ha^{-1} at 50% C content. Malaysian forests have C density ranging from 100 to 160 Mg ha^{-1} and from 90 to 780 Mg ha^{-1} in vegetation and soils, respectively (Murdiyarso and Wasrin, 1995;

Noordwijk *et al*., 2000, Hairiah and Sitompul, 2000; Lasco *et al*., 1999; Lasco *et al*., 2000; and Abu-Aker, 2000 cited in Lasco *et al*., 2002). Changes in total carbon stocks in forest stands can be assessed by direct measurements of net sources and sinks over periods of 1 or more years (Fuguda *et al*., 2003).

2.2.2 Reforestation

Reforestation and afforestation play an important role in mitigating potential climate change caused by increasing atmospheric CO_2 concentrations and have been taken as possible options for meeting developed country greenhouse gas targets under Kyoto Protocol of the UNFCCC (Schulze *et al*., 2000). Between 1960 and 1990, Asia has lost nearly a third of its tropical forest cover to deforestation (FAO, 2001). In recent years reforestation of degraded and abandoned tropical pastures has been proposed as a measure to mitigate increasing atmospheric CO_2 levels (Montagnini and Porras 1998, and Silver *et al*. 2000). The area of forest plantations increased with about 14 million hectares during 2000-2005, or 2.8 million hectares per year, 87 percent of which are productive forest plantations (FAO, 2005). Reforestation has been proposed as means to help offset C losses through the accumulation and long term storage of C in plant biomass and soil organic matter. Significant amounts of C can accumulate in plants and soils within the first 20 years of forest regrowth (Silver *et al*., 2000). Silver *et al*. (2000) estimated that reforestation of abandoned tropical agricultural land and pasture sequesters C in the soil at a rate of 130 g C m^{-2} yr^{-1} for the first 20 year, and then at an average rate of 41 g C m^{-2} yr^{-1} for the following 80 year. Unlike aboveground biomass, which always increases with reforestation, soil C from the previous land use can be gain or lost simultaneously with the reforestation (Rhoades *et al*. 2000; and Silver *et al*. 2004). Significant soil C can accumulate with reforestation and that there are strong legacies of pasture use and reforestation in plant community structure and rates of plant C sequestration (Silver *et al*., 2004). The use of mixed plantations with species of different rotation times may allow the system to retain the C for longer periods of time than in a monoculture. Overall, species in mixed plantings had higher values of C sequestration than pure plantings (Redondo-Brenes and Montagnini, 2006).

2.2.3 Agricultural land

Agricultural systems contribute to carbon emissions through several mechanisms: (i) the direct use of fossil fuels in farm operations; (ii) the indirect use of embodied energy in inputs that are energy-intensive to manufacture (particularly fertilizers); and (iii) the cultivation of soils resulting in the loss of soil organic matter. On the other hand, agriculture is also an accumulator of carbon, offsetting losses when organic matter is accumulated in the soil, or when aboveground woody biomass acts either as a permanent sink or is used as an energy source that substitutes for fossil fuels (Pretty and Ball, 2001).

When cropland is abandoned, carbon re-accumulates in vegetation as the land reverts to the natural ecosystem. The greater the biomass of the returning ecosystem, the greater the long-term carbon sink associated with recovery (Houghton and Goodale, 2004). In the short term, however, the magnitude of the annual sink for a particular parcel of land will vary with rate of recovery, which may be affected by the intensity of previous land use or by biophysical factors such as distance from seed source, herbivory, soil fertility, or climatology (Kozlowski, 2002). The rate of recovery of vegetation can also depend on both climate conditions (growing season length) and soil type (Johnson *et al*., 2000). Soil carbon may also re-accumulate after abandonment of cultivation, although the rates of carbon accumulation in mineral soil are rather modest (Post and Kwon, 2000), especially when compared to the much faster rates of carbon accumulation in vegetation, surface litter, or woody debris (Barford *et al*., 2001; and Hooker and Compton, 2003). Globally, carbon accumulation in mineral soils recovering from past tillage is likely to amount to less than 0.1 Pg C yr^{-1} (Post and Kwon, 2000). Grandy and Robertson (2007) results support theories that agricultural soil C losses near the soil surface can be partially reversed by using less intensive cultivation and manipulating plant community dynamics. We found that the highest C accumulation rates occur in perennial cropping systems and early successional ecosystems.

A change in agricultural practice can increase carbon sequestration in agricultural soils. Agricultural ecosystems differ from forest ecosystems in that belowground carbon stocks dominate above-ground carbon stocks, there are no long-lifetime products to consider, the energy and CO_2 implications of annual inputs to production play a larger role, product substitution takes a very different role, and the associated contribution of other greenhouse gases than CO_2 is more important (Marland *et al*., 2003). If productivity increases and cultivated land is abandoned and allowed to revert to grassland or forest, an accumulation of 335 kg C ha^{-1} yr^{-1} is expected in the soil (Post and Kwon, 2000) and emissions from agricultural machinery and inputs on that land cease. Thus, agricultural land is added to or released from crop production there will be changes in greenhouse gas emissions and soil carbon stocks on that land.

There have been studies relating to changes in carbon stock in different land use types. Tropical forests and cropland estimated to have 140.45 and 1.87 Mg C ha^{-1} in vegetation and 122.72 and 80.00 Mg C ha^{-1} in soil carbon pools down to 1 m depth (IPCC, 2000). The SOC pool can be depleted by 15-40% in a 2-year period to 1 m depth when tropical forest is converted to agricultural land use (Ingram and Fernandes, 2001) or as much as 50-75% (Lal, 2004; and Post and Kwon, 2000). In the reforested ecosystem, recent study showed that the total soil C pool (0-60 cm depth) was larger than the aboveground C pool, and there was more soil C in the forest (102 ± 10 Mg ha^{-1}) than in an adjacent pasture of similar age (69 ± 16 Mg C ha^{-1}). Forest soil C (C_3-C) increased at a rate of 0.9 Mg C $ha^{-1}yr^{-1}$, but residual pasture C (C_4-C) was lost at a rate of 0.4 Mg C $ha^{-1}yr^{-1}$, yielding a net gain of 33 Mg C ha^{-1} as a result of 55 years of forest regrowth. Aboveground C accumulated at a rate of 1.4 ± 0.05 Mg C $ha^{-1}yr^{-1}$, to a total of 80 ± 3 Mg C ha^{-1} (Silver *et al*., 2004).

Bonino (2006) estimated carbon stock on the basis of components aboveground biomass and soil (20 cm depth) in different land-use type in Argentina. The results showed land-use change produced severe losses in the carbon stocks. It decreased from 64.96 Mg C $ha^{-1}yr^{-1}$ in the primary forest to 36.48 Mg C $ha^{-1}yr^{-1}$ in the secondary forest and to 23.66 Mg C $ha^{-1}yr^{-1}$ in the shrubby grassland. Fitzsimmons *et al*. (2004) investigated carbon stock (aboveground biomass and soil organic carbon down to 45 cm depth) in different land-use type in Canada. They found that carbon stock in the forest sites (158 Mg C $ha^{-1}yr^{-1}$) was significantly greater ($P < 0.005$) than the pasture (63 Mg C $ha^{-1}yr^{-1}$) and the cultivated fields (81 Mg C $ha^{-1}yr^{-1}$). Soil organic carbon was larger than aboveground carbon for all sites and differences in carbon stocks between the forested and deforested sites were primary the result of differences in aboveground biomass.

2.3 Climate change and greenhouse emission in Thailand

Thailand's emissions are a small fraction of global emissions (about 0.6 percent of the total emissions), its own reduction efforts will not be effective if they occur in isolation (Climate Change Coordinating Unit, 2006). However, Thailand recognizes the significance of climate change and global warming, therefore the committed to being a party to the UNFCCC on 28 December 1994. Thailand signed its support for the Kyoto Protocol on 2 February 1999, ratified on 28 August 2002. Thailand is a non-Annex I country under the 1997 Kyoto Protocol, meaning it has no binding obligation to reduce its carbon emissions. Therefore, Kyoto Protocol established the Clean Development Mechanism (CDM) to facilitate sustainable development projects in developing countries that would reduce greenhouse gas (GHG) emissions. Thailand appointed the Ministry of Natural Resources and Environment as Coordinator and also assigned the NACDM (National Authority for Clean Development Mechanism) to liaise with foreign countries interested in CDM investment in Thailand (Domrongphol, 2005).

The CDM of the Kyoto Protocol will allow afforestation and reforestation projects to be established in developing countries to assist industrialised countries reach their emission reduction targets. The projects must be sustainable, and the consequences of the projects on other sites and carbon pools must be assessed. Plantations can be established for different environmental and social benefits, including storage of carbon. The most cost-effective plantings for carbon sequestration may often be those where financial subsidies to sequester carbon can be combined with profits from commercial wood growing. Planting trees may also have additional benefits, such as preventing erosion and increasing biodiversity. The soil will contain significant amounts of organic carbon. It can take several decades before biomass pools store as much carbon as is already stored in soil organic matter. It is, therefore, important to protect, and, if possible, increase this large reservoir in the soil. (Kirschbaum, 2003).

Deforestation in Thailand is causing serious ecological, social, and economic problems, in addition to contributing to global warming. In order to reduce these impacts and control GHG emissions, Thailand is intensifying its efforts to control deforestation and reforest some areas that have already been deforested. In principle, Thailand supports the idea that reduced emissions of carbon from deforestation should be rewarded on a national basis through an international system. In addition, any increases in net forest area should be subject to compensation, not merely reductions in the rate of deforestation. Loss of biomass within forest may be a significant contributor to carbon emission, but is not included in simple a real estimates of deforestation (UNESCAP, 2007).

2.4 Land use, land-use change and forestry in Thailand

The study on climate change due to land use, land-use change and forestry (LULUCF) in Thailand, it is concerned with anthropogenic activities of “sink” which has evolved to cover emissions and removals of greenhouse gases resulting from LULUCF. Activities in the LULUCF sector are under Article 3.3 of the Kyoto Protocol of the United Nations Framework Convention on Climate Change (UNFCCC), which is the Parties decided that greenhouse gas removals and emissions through through certain activities namely, *afforestation* and *reforestation* since 1990 that are accounted for in meeting the Protocol’s emission targets. Conversely, activities that deplete forests, namely *deforestation*, will be subtracted from the amount of emissions that an Annex I Party may emit over its commitment period. Through Article 3.4 of the Protocol, Parties decided that additional activities could be added to this list in the future such as forest management, cropland management, range management, wetland management, settlement and others, etc (Luangjame, 2005). Preparation of this initial national communication was guided by the Guideline for Initial Communication for Non-Annex I Parties. The estimation of national greenhouse gas inventory for 1994 used the 1996 Revised Guidelines of IPCC as a reference. Gross emissions of carbon dioxide (CO_2) in Thailand in 1994 were estimated at 241 Tg. The energy supply sector accounted for more than half of the gross CO_2 emissions in 1994, while the land use change and forestry sector accounted for about 41%. Other greenhouse gas emission, land use changes and forestry were the main CO_2 emitters (94 percent) (table 2.3) (Ministry of Science, Technology and Environment, 2000 cited in Chittachumnonk, 2003).

Table 2.3 Thailand’s national greenhouse gases inventory (Gg).

Greenhouse Gas Source and Sink Categories	CO_2 Emission	CO_2 Removal	CH_4	N_2O	NO_X	CO
Total emission and removals	241,030.50	-39,101.60	3,171.35	55.86	286.65	555.11
Land use change and forestry	99,577.40	-39,101.60	59.57	0.41	14.80	521.21
A. Changes in forest and other woody biomass stocks	40,180.50	-39,101.60	-	-	-	-
B. Forest and grassland conversion	59,396.80	-	59.57	0.41	14.80	521.21

Land use change effects on carbon emission in soil. Panuthai *et al*. (2005) reported that the amounts of annual CO_2 released by CO_2 released by soil in dry evergreen and mixed deciduous forests were 0.138 and 0.163 mg CO_2 m^{-2} s^{-1} or 3.142 and 3.698 μ mol m^{-2} s^{-1} respectively. Apparently, the variation in the amounts of soil CO_2 release reflects difference in litter fall, soil characteristics and vegetation types (Panuthai *et al*., 2005). Comparison to different land use types, the CO_2 emission from natural forest (dry evergreen forest), reforest (*Acacia mangium*) and agricultural (maize) land-use types was 8.13, 11.65, and 9.97 ton C ha^{-1} respectively, the range of CO_2 emission from these land-use types was around 12-17 ton C ha^{-1} y^{-1} (Chidthaisong and Lichaikul, 2005).

Dynamics of Thailand forest resource change throughout the country. Forest covered over 60% of the land area in 1953, but by 2000 this had fallen to less than 30%. Between 1990 and 2000, the annual loss of forest cover was an estimated 112,000 hectares, a deforestation rate of 0.7% (FAO, 2005b). For the forestry sector on the land use, land-use change and forestry (LULUCF) activities, afforestation and reforestation are campaigned around the kingdom. According to the forestry policy present in the past, present, and the future, Thailand followed the National Economic and Social Development Plan (NESDP) since the fifth plan (1982-1986) till at present of the ninth plan (2002-2006) and the national forestry policy in 1985 to keep the forest at least 40% of the total land country areas of 513,115 km^2. This amounts of the areas are 25% for conservation forest and 15% for economic forest. There is issued a forestry master plan of national forest resource improvement for the year 2004-2013 under the policy and plan of the national environmental quality promotion during 1997-2016 that the country needs to have forest resources at least 50% of the total country and of this 30% for conservation and 20% for economic forest areas (Dulyapach and Luangjame, 2003).

According to the Royal Forest Department’s satellite data acquired in 2004, Thailand’s forest area continued to decline to 167,591 square kilometers, compared to 170,111 square kilometers in 2000. The contraction mainly reflected illegal logging and illegal encroachment of forest land for agriculture and tourism, particularly in the north and the south. Presently, total forest area accounted for about 32.7 percent of total land area (United States Department of Agriculture [USDA], 2006). Therefore, Thailand has to reforest and afforest in order to increase forest area for 17%. However, this master plan is set to plant in conservation forest 500,000 rai per year (80,000 ha), community forest 500,000 rai per year (80,000 ha) and economic forest 600,000 rai per year (96,000 ha) and totally 1.6 million rai per year (256,000 ha) or 16 million rai (2.56 million ha) for 10 years of the period of the plan (Dulyapach and Luangjame, 2003). The new ministry of natural resource and environment has taken over the responsibilities for protecting forest, protected areas and national parks, community forests and watershed management unit while the remnant Royal Forestry Department continues to hold responsibility for commercial activities grouped under economic forestry, including silviculture, reforestation and forest utilization throughout of Thailand (Brown and Durst, 2003).

Up to now, many people still live on land classified as forest under the National Parks Act (1961) and the Wild Animal Reservation and Protection Act (1992). Increasing public awareness the environment, decentralization pressure and empowerment to local people should play an active role in natural resource management in Thailand. In the year 2005, over 5,331 villages have registered their community forest programs with the Royal Forestry Department (2000-2005 record, 0.7% of the total number of villages in the country). These villages are managing community forests, which in total cover an area of approximately 1,229,170.49 rai or 196,667.28 hectares in both National Forest Reserves (705,432.34 rai or 112,869.17) and other forests according to the Forest Act B.E. 2484 (1941) (523,738.15 rai or 83,798.10 ha). The area under community forest management accounts for about 1.16% of total forest areas or 0.38% of total country land area (Wichawutipong, 2005). Thailand’s forest area diminished from 53.33 percent of the total land area in 1961 to 25.13 percent in 1998 (Lakanavichian, 2001), increasing up to 32.66 percent in 2004 (Royal Forest Department, 2004). The status and change of total forest area in each region show in table 2.4 (Royal Forest Department, 1998; 2004; and Green World Foundation, 1999).

Table 2.4 Forest area by region, 1976, 1989 and 2004.

Region	1976		1989		2004	
	Area (million ha)	% of total	Area (million ha)	% of total	Area (million ha)	% of total
North	10.23	19.94	8.02	15.63	9.21	17.94
Central	3.45	6.72	2.50	4.87	2.95	5.75
Northeast	4.15	8.09	2.36	4.60	2.81	5.48
South	2.01	3.92	1.46	2.85	1.79	3.50
Total	19.84	38.67	14.34	27.95	16.76	32.66

There were several reasons for the reported increase in forest area, which was based on the interpretation of satellite images; a ground survey verification has yet to be carried out. Jarupath *et al*., (2005, cited in Luangjame, 2005) studied the change of forest types effected to global climate change by using satellite imagery. They reported that Thailand's forest area decreased from 33.14 percent of the total country (106,319,240 rai or 17,011,078 ha) in 2000 to 32.68 percent of the total country (104,744,357 rai or 16,759,097 ha) in 2004, total loss 1,574,883 rai (251,981 ha) or average loss 393,721 rai (62,995) per year. The forest area and aboveground carbon show in table 2.5.

Table 2.5 Forest areas and carbon aboveground in 1990, 2000 and 2004

Forest type	Area (km^2)			Aboveground carbon (million ton)			Carbon (ton/km^2)
	1990 (30.52%)	2000 (33.14%)	2004 (32.67%)	1990	2000	2004	
Evergreen Forest	67,861.00	53,108.01	54,045.38	2,282.96	1,789.74	1,821.33	33,700
Mixed Deciduous Forest	33,929.00	89,205.03	89,916.03	902.51	2,372.85	2,391.77	26,600
Dry Dipterocarp Forest	48,930.00	18,569.52	20,413.24	616.52	233.98	257.21	12,600
Pine Forest	2,162.00	462.08	453.59	34.59	7.39	7.26	16,000
Mangrove Forest	2,872.00	2,452.55	2,758.05	57.44	49.05	55.16	20,000
Plantation	-	6,313.59	-	-	126.27	-	20,000
Inundated forest	846.00	-	-	8.46	-	-	10,000
Total	156,600.00	170,110.78	167,132.70	3,906.44	4,579.28	4,532.73	-

Although commercial logging was banned, deforestation for agricultural practices still continues being a problem in Thailand. In recent years, attempts to restore the loss of forested land have led to a new reforestation policy/plan in Thailand. Reforestation in Thailand has been practiced since 1906 when teak (*Tectona grandis* L.f) was planted in the form of taungya plantations. From then until 1960 small areas were planted annually by forest Industry Organization (FIO). Accomplishments were very modest; only about 36,273 rai (5,804 ha) were planted by 1960, of which 92 percent was teak. The reforestation program gradually expanded after 1961. The cumulative area planted reached 5,436,368.75 rai (869,819 ha) in 1996 (FAO, 1998). Based on area planted, the four most important tree species are teak (*T. grandis* L.f), followed by two local pines (*Pinus kesiya* and *P. merkusii*) and a eucalypt (*Eucalyptus camaldulensis* Dehnh.) (Uthaiwan, 1998). Teak (*Tectona grandis* L.f.) and Eucalyptus (*Eucalyptus Camaldulensis* Dehnh.) plantations often are reported in biomass and carbon estimations. Teak, formerly a common deciduous tree species distributes throughout the lowland forests of northern Thailand, has been virtually eliminated by forest exploiters in the wildlife sanctuary for many decades (Putiyanan and Maxwell, 2007). Moreover, teak is one of the most valuable timber (Motoshi *et al*., 2005) and has long been one of Thailand’s exported products. Eucalyptus in particular was promoted in the National Forest Policy as a wood fiber source for a nascent pulp and paper industry. Areas of National Reserve Forests were leased to plantation firms and farmers were encouraged to plant eucalyptus as an alternative source of income to the low returns available from rice and cassava farming (Laemsak, 2002). Since 1965, the reforestation in Thailand is a strategy to restore forest ecosystem. The Royal Forest Department’s Watershed Management Division has taken measures to rehabilitate degraded steep lands in watersheds through reforesting and the establishment of forest villages. The forest area managed primarily for the protection of soil and water is estimated to be about 9.32 million hectares (Royal Forest Department, 2002). The Royal Forest Department reported the total reforested area and increased from 8,157.44 ha to 1,086,010.6 ha in 1906 to 2004 (Royal Forest Department, 1998; and 2004). The amount of carbon uptake also depends on types of trees planted. For example, about 37 percent of reforested areas in Thailand are planted using teak (*Tectona grandis* L.f.), while about one-third are planted using eucalyptus (*Eucalyptus camaldulensis* Dehnh.), a particular species of fast growing trees preferred by the private sector. Both teak and eucalyptus species are estimated to yield between 15-17 tonnes of dry matter per hectare per year (t-dm yr^{-1}), more than twice that for slow-growing species of trees (6.8 t-dm yr^{-1}) (Office of Environmental Policy and Planning [OEPP], 2000).

For Thailand, few study of land use effect on carbon emission. Panuthai *et al.* (2005) studied soil CO_2 emissions in the Sakaerat dry evergreen forest and the Maeklong mixed deciduous forest. They reported that the amounts of annual CO_2 released from soil in dry evergreen and mixed deciduous forests were 0.138 and 0.163 mg CO_2 m^{-2} s^{-1} or 3.142 and 3.698 μ mol m^{-2} s^{-1} respectively. Apparently, the variation in the amounts of soil CO_2 release reflects difference in litter fall, soil characteristics and vegetation types (Panuthai *et al.*, 2005). Comparison to different land use types, the CO_2 emission from natural forest (dry evergreen forest), reforest (*Acacia mangium*) and agricultural (maize) land-use types was 8.13, 11.65, and 9.97 ton C ha^{-1} respectively, the range of CO_2 emission from these land-use types was around 12-17 ton C ha^{-1} y^{-1} (Chidthaisong and Lichaikul, 2005). Overall, various forest types in Thailand have a C density in aboveground biomass ranging from 72 to 182 Mg ha^{-1} (Boonpragob, 1998).

2.5 Secondary forest

Secondary forests are defined here as “forests regenerating largely through natural processes after significant human disturbance of the original forest vegetation at a single point in time or over an extended period, and displaying a major difference in forest structure and/or canopy species composition with respect to nearby primary forests on similar sites” (Chokkalingam *et al.*, 2000). Tropical secondary forests are those forests that have developed after clearance (usually by humans) of the original natural forest. Although not appearing as such in statistics, tropical secondary forests occur throughout the tropics, and the area is extensive and increasing rapidly. Tropical secondary forests are usually an integral part of local and regional land use and production systems and inhabited by communities (FAO, 2003). Secondary vegetation appears to be a chaotic wilderness of several trees, shrubs, climbers and tall herbaceous plants, is always more or less unstable and consists of successional stages (Blaser and Sobagal, 2002 cited in FAO, 2003). Secondary forest in fallow land was developed for the purpose of restoring the land for cultivation again. In swidden system, secondary forests are part of rotational systems, but can also develop on the intensively used fields of pioneer swiddeners. In very remote areas, where climax forests occur and where population pressure is not high, the secondary forest regeneration in the sparsely distributed small gaps is rather rapid (Ramakrishnan and Kushwaha, 2001). It's clear that the composition of the original vegetation, site conditions, and land use techniques determine the development, structure and composition of these forests. However, comparison with primary forests is difficult because remnant stands of original forests are often located on hilltops or ridges, sites that differ considerably from slopes preferred for farming (Schmidt-Vogt, 2001). Ruankaew (2004) reported that although secondary vegetation in fallow land of shifting cultivation has attained similar levels of area and tree diversity, species composition remains distinct from that of residual original forest.

In terms of current C storage, fallow forest is likely to affect C dynamics. Annual carbon (C) sequestration rates in tropical forest fallow are estimated to account for 25–90% of C losses due to biomass burning in forests (Naughton-Treves, 2004). Tschakert *et al*. (2007) reported the aboveground carbon stocks (not including soil C) in fallow systems about 23-60 t ha^{-1} in eastern Panama, which also corresponded to the Alternatives to Slash-and-Burn (ASB) benchmark sites in Indonesia, Brazil, Thailand, and Cameroon, with means ranging from 6 to 131 t ha^{-1} for 4-23 year fallows (Palm *et al*., 2000 cited in Tschakert *et al*., 2007). In addition to global environmental services such as C storage and biodiversity conservation, secondary forests and forest fallows contribute to improve local ecological conditions, including erosion control and watershed protection (Smith and Scherr, 2003).

2.6 Study area

2.6.1 Location and natural resources

The study area is located in Nam-Hean Watershed Management Unit, Nam-Yao sub-watershed, Nan province (19°05′10″N, 100°37′02E″). The land area is approximately 19,000 ha. The area is composed of the 3 sub-watersheds: Nam Hean, Nam Rim and Nam Ki Sub-watershed which covered 12.30%, 40.60% and 47.10% of total area respectively. The elevation ranges from 215 to 1,674 m a.s.l. The soil parent material consists of sand stone, shale stone and lime stone, soils are mainly Red Yellow Podzolic soils and Reddish Brown Lateritic soils. The average air temperature is 16.9 °C during the dry season and 32.5 °C during the wet season. Average annual precipitation is 1,405 mm. The land cover types consist of evergreen, and mixed deciduous forests, reforestation, orchards, corn fields, rice paddy fields and small part of other crop cultivations (Royal Forest Department, 1998).

2.6.2 Land use

The most of area is mountain and steeply slopping. Environment degradation of watershed was identified as the main problem in this area. At that time, the natural forest has been severely degraded during the past thirty years due to legal and illegal logging, shifting agriculture, and uncontrolled forest fires. The two dominant land use activities in this area are forestry and agriculture. In 1985, land use was divided into forest (84.64% of total area) and agricultural land (12.36% of total area). Although, forest was a high proportion of area, natural and secondary forest, and forest plantation covered only 8.76% and 3.99% of total forest, most of forest (74.89%) was degraded forest (Rakpanichseang, 1985) (Table 2.6). In agricultural land, approximately 87.67%, 7.09% and 5.24% of total area is cultivated with corn, rice fields and other grain crops, respectively (Padklang, 1999). Because of the severe deterioration of forest conditions, reforestation initiatives have become a high priority to the Royal Thai Government. Science the 1970s, reforestation activities have been implemented in the degraded area of Nam Hean watershed. Farmland and heavily eroded areas were replanted with fruit and economic trees by hill tribes and Thais. Government plans to reforest depleted areas by planting native and exotic species for the purpose of watershed conservation were designed and managed (Royal Forest Department, 1999).

Although, forest area increased by preserved and improved degraded forest as protection forest for nature conservation, recreation and environmental quality protection in this area, the estimates of the elasticity reveal that forest and agricultural land-use shares are much more responsive to agricultural returns than to forest. From

1985 to 2004, forest area and agricultural land increased to 20.00% and 25.26% of total area, while reforested area expanded to 4,177 ha (Table 2.6, Figure 2.1).

Table 2.6 Land use in study area

Year 1985			Year 2004		
	Area (ha)	% of total area		Area (ha)	% of total area
Natural and Secondary forest *	1,665	8.76	Natural and Secondary forest	3,800	20.00
Forest degradation**	14,229	74.89	Fallow land****	6,223	32.75
Forest plantation***	758	3.99	Forest plantation	4,177	21.99
Agriculture	2,349	12.36	Agriculture	4,800	25.26

Source: Nam Hean Watershed Management Unit, 2004

* Natural forests are forests composed primarily of indigenous tree species and not classified as a forest plantation. (FAO, 2001), Secondary forest is a woody vegetation regrowing on land that was largely cleared of its original forest cover. Secondary forests commonly develop naturally on land abandoned after shifting cultivation, settled agriculture, pasture or failed tree plantations. Secondary forest may also be the result of natural forest regeneration after catastrophic natural disturbances such as wildfire, storms, landslides and floods (ITTO, 2002).

** Forest degradation is changes within the forest that negatively affect the structure or function of the stand or site, and thereby lower its capacity to supply products and/or services (FAO, 2000).

*** Forest plantation is a forest established by planting and/or seeding in the process of afforestation or reforestation. They are either of introduced species (all planted stands), or intensively managed stands of indigenous species, which meet all the following criteria: one or two species at plantation, even age class, regular spacing (FAO, 2001).

**** Fallow land refers to land, which the holder chose not to cultivate during the reference year, with the intention of recultivating at a later date. Land, which had been left idle for five years or more, was included under another land use category. Fallow land is generally of two types: land that has been left idle in the current crop season to improve the productivity of the land; and land that is left fallow for a longer time period and for which no cultivation activity has been planned. (FAO, 2003).

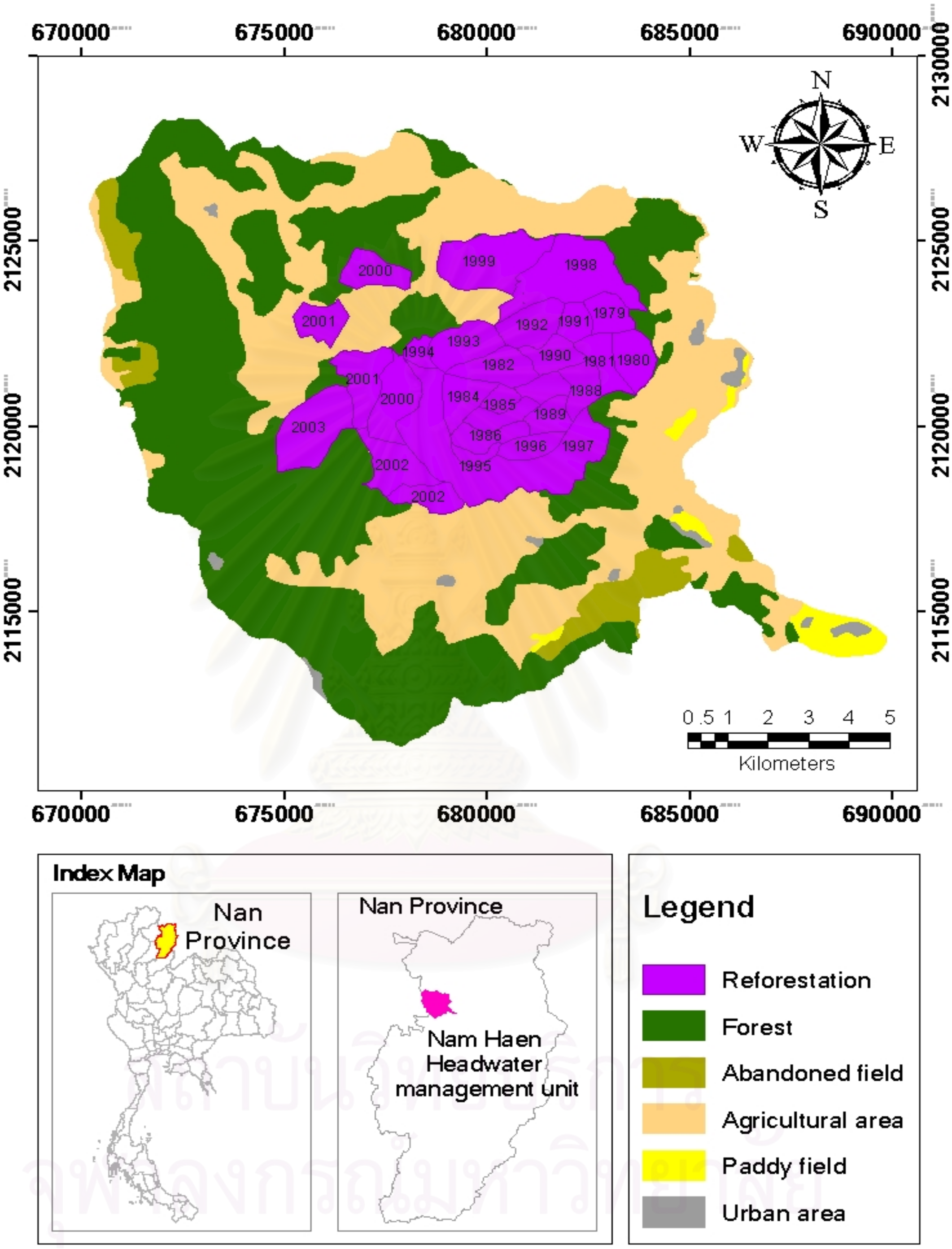


Figure 2.1 Location of the study

CHAPTER III

ABOVEGROUND CARBON AND PLANT COMMUNITY

ABSTRACT

In terrestrial ecosystems, aboveground carbon often produces a significant component of carbon stocks. This study was conducted to assess aboveground carbon stocks in different land-use type in the Nam Yao sub-watershed, northern Thailand. Carbon stocks in live aboveground biomass and litters were measured in a heterogeneous land use. In the forest, the average aboveground carbon in hill evergreen forest was 156.93 ± 12.51 Mg C ha^{-1}. In the reforestation, the average aboveground carbon in the 26-year-old reforestation was 42.93 ± 6.35 Mg C ha^{-1}. In agricultural land, the orchard (*Litchi chinensis* Sonn. spp.) stored carbon at the average of 8.17 ± 0.75 Mg C ha^{-1}. Of these amounts, the majority of aboveground carbon represented in live biomass which clearly stored more than 94.62%, 88.95% and 97.52% in the forest, followed by reforestation and agricultural land, respectively. It indicated that total aboveground carbon (TAGC) was dominated by aboveground vegetation carbon while litter carbon was a small fraction of total aboveground carbon.

Keywords: aboveground carbon; land-use type; litter carbon, northern Thailand

3.1 INTRODUCTION

In the tropics, biomass is of primary important indicator, it allows calculation of the amount of carbon lost with deforestation (Houghton, 2005). Tropical forest biomass estimates are a useful way to assess the forest carbon stocks and emissions to the atmosphere during deforestation and changes in land cover (Malhi and Grace, 2000). Historically, the most important change of land use was the expansion of agriculture, with most of the conversion to agriculture occurring in the tropics during the last 150 years (Houghton, 1999). Changes of land use and land cover result in the loss of carbon stocks from vegetation. Conversion of natural forests to tree plantations and perennial crops reduce C density by at least 50% relative to natural forests (Lasco, 2002). Erb (2004) also indicated that the main cause of the reduction in aboveground carbon stocks is the conversion of forest ecosystem to managed ecosystems, such as agricultural areas and grassland. In addition to ecosystem conversion, the management of forests substantially contributes to the reduction of aboveground carbon stocks.

With this regard, the reforestation through plantation on abandoned and degraded agricultural lands in the tropics has been proposed as a means to help offset increasing carbon emissions to the atmosphere (Silver *et al*., 2000). Plantation forests and secondary forests are becoming dominant components of many tropical forest in land-use type. The plant community composition and structure of reforested ecosystems naturally differs from mature forest ecosystems. Reforestation may lead to changes in community composition due to the design and species selection. For instance, the plantations of single tree species are often considered to be associated with the lowest biological diversity among forests (Kamo *et al*., 2002). Silver *et al*. (2004) found that the diversity, degree of dominance, or composition had a few discernable impacts on aboveground carbon pool. In Nam Yao sub-watershed, northern Thailand, the degraded forests were reforested to restore the forest ecosystem by the Restoring Head Water Ecosystems Project (Royal Forest Department) from 1979 to 1994 and the Upper Nan Watershed Management Project (Royal Forest Department and Danish Cooperation for environment and Development) from 1994 to 2000. Various species were planted in degraded natural forests. Mainly, there are composed of different single exotic species.

This study aimed to determine the potential of carbon sequestration in different land-use types. Specific objectives of this study were to (i) assess changes in aboveground carbon pool in different land-use type, and (ii) assess changes in plant community after conversion forest to reforestation and agricultural land.

3.2 METHODS

3.2.1 Study site

This study was carried out in the Nam Hean Watershed Management Unit, Nam Yao sub-watershed, Nan province (19°05'10"N, 100°37'02"E). The land area is approximately 19,000 ha. The study was conducted in three main land-use types including forests, reforestations, and agricultural lands. The site collection was designed regarding Table 3.1 (Figure 3.1-3.3).

The three forest sites are located in Pa Nam Yao and Pa Nam Suad National Reserves Forest, where natural hill evergreen forest (HEF), dry evergreen forest (DEF) and mixed deciduous forest (MDF) are found. The other two sites were conducted in managed forest, conservation for head water in protected forest, namely Num Krai conservation forest (CSF) and community-managed for forest conservation namely Ban Hoak community forest (CMF).

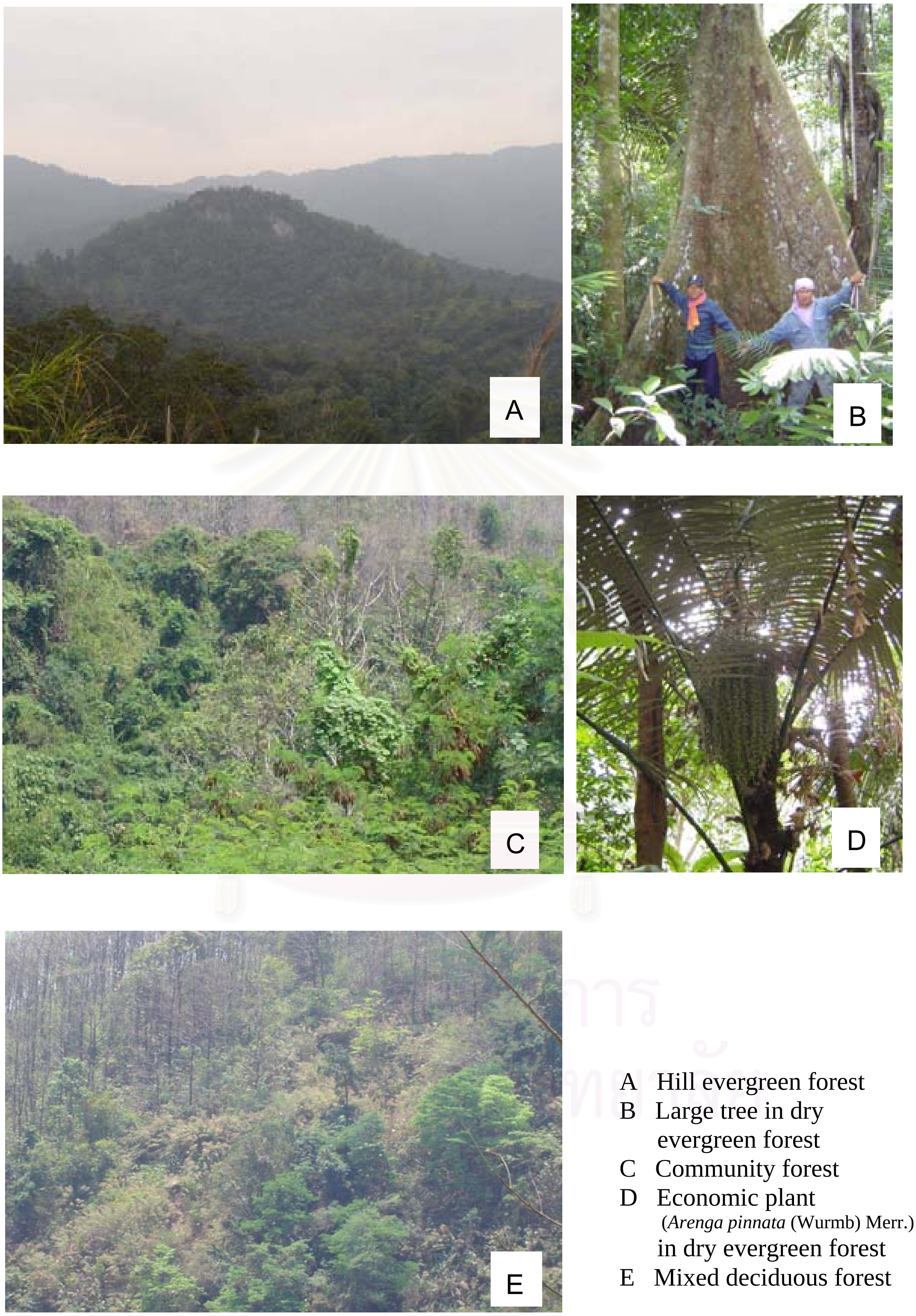
The five reforestation sites were established in area of Nam Haen Watershed Management Unit. The reforestation sites included plantation which planted *Gmelina aborea* Roxb. in 1979 (RF26), *Eucalyptus camaldulensis* Dehn. and *Tectona grandis* Linn. in 1986 (RF19), *Tectona grandis* Linn. in 1991 (RF14), *Tectona grandis* Linn., *Pterocarpus macrocarpus* Kurz., *Afzelia xylocarpa* (Kurz) Craib, *Acacia catechu* (L.f.) Willd, and *Pyrus malus* L. in 1995 (RF10), *Tectona grandis* Linn., *Pterocarpus macrocarpus* Kurz., *Afzelia xylocarpa* (Kurz) Craib, *Acacia catechu* (L.f.) Willd, and *Bauhinia vriegata* L. in 1996 (RF9).

The five agricultural sites are located on private lands that have been under continuous cultivation for producing small grains and corn for 30-50 years. All of the agricultural sites were cleared prior to 1957. All landowners presently practice conventional tillage and also apply chemical fertilizer. The first site (FL) is fallow land (5-6 years), allowed to be used for agricultural propose, has been cultivated intensively with corn. The second site (LT) is orchard (*Litchi chinensis*) which was planted in 1996. The third site (Rice) is paddy fields (*Oryza sativa* L.). The last two sites (Corn1 and Corn2) are corn fields (*Zea mays* Linn.), which corn cultivation as a major cash crop is dominated in this area.

All sites for each treatment group were sampled two times from November to December 2005 and from January to March 2006.

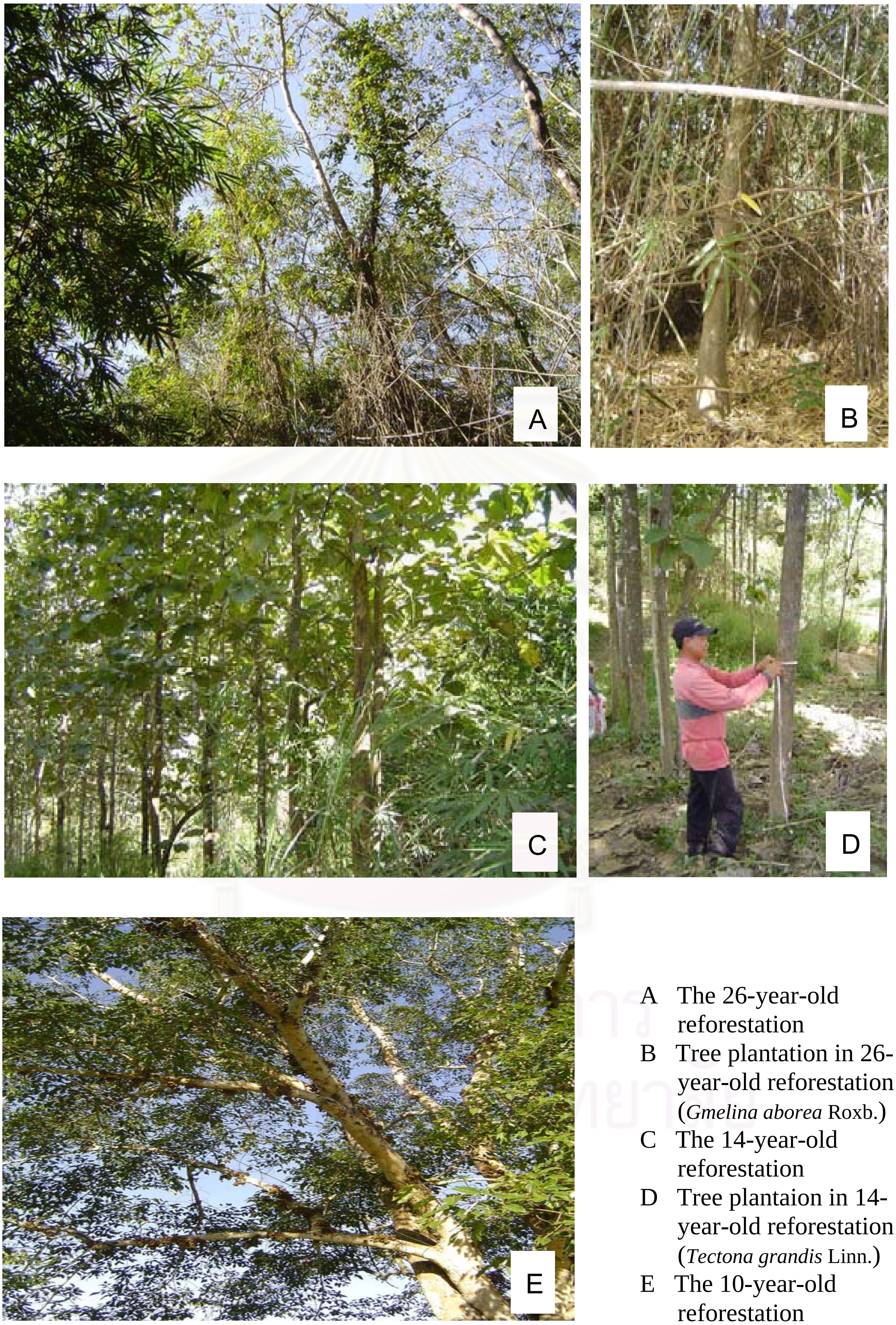
Table 3.1 Study sites in Nam Haen Watershed Management unit area

Sites	Location	Type/vegetation	Plot size (m^2)	Plot Number
Forest				
HEF	47Q 0672295 UTM 2126899	Hill evergreen forest	50 x 50	8
DEF	47Q 0672344 UTM 2125649	Dry evergreen forest	50 x 50	8
MDF	47Q 0675457 UTM 2118240	Mixed deciduous forest	50 x 50	8
CSF	47Q 0680732 UTM 2115809	Mixed deciduous forest	50 x 50	8
CMF	47Q 0685006 UTM 2116906	Mixed deciduous forest	50 x 50	8
Reforestation				
RF26	47Q 0684082 UTM 2122527	*Gmelina aborea* Roxb.	50 x 50	4
RF19	47Q 0680748 UTM 2119676	*Eucalyptus camaldulensis* Dehn. *Tectona grandis* Linn.	50 x 50	4
RF14	47Q 0683003 UTM 2122381	*Tectona grandis* Linn.	50 x 50	4
RF10	47Q 0679903 UTM 2119368	*Tectona grandis* Linn. *Pterocarpus macrocarpus* Kurz. *Afzelia xylocarpa* (Kurz) Craib. *Acacia catechu* (L.f.) Willd, and *Pyrus malus* L.	50 x50	4
RF9	47Q 0680990 UTM 2119752	*Tectona grandis* Linn. *Pterocarpus macrocarpus* Kurz. *Afzelia xylocarpa* (Kurz) Craib. *Acacia catechu* (L.f.) Willd, and *Bauhinia vriegata* L.	50 x 50	4
Agriculture				
FL	47Q 0683820 UTM 2123305	Fallow land (5-6 years)	50 x 50	4
LT	47Q 0673679 UTM 2126388	*Litchi chinensis* Sonn. spp.	50 x50	4
Rice	47Q 0681248 UTM 2117440	*Oryza sativa* Linn.	1 x 1	10
Corn1	47Q 0673788 UTM 2126210	*Zea mays* Linn.	1 x 1	10
Corn2	47Q 0681215 UTM 2124023	*Zea mays* Linn.	1 x1	10



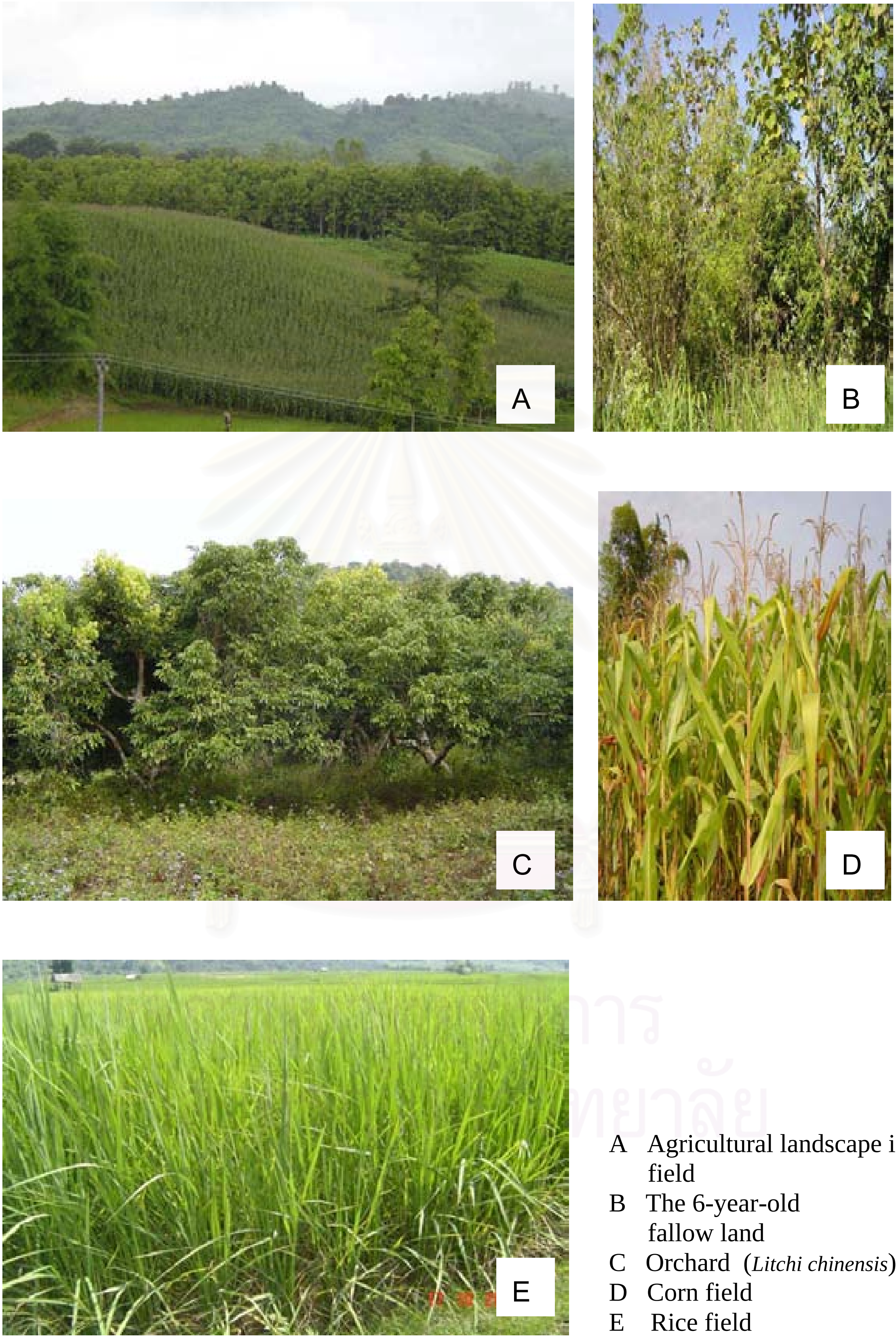
A Hill evergreen forest
B Large tree in dry
evergreen forest
C Community forest
D Economic plant
(*Arenga pinnata* (Wurmb) Merr.)
in dry evergreen forest
E Mixed deciduous forest

Figure 3.1 Forest land-use types



A The 26-year-old reforestation
B Tree plantation in 26-year-old reforestation (*Gmelina aborea* Roxb.)
C The 14-year-old reforestation
D Tree plantaion in 14-year-old reforestation (*Tectona grandis* Linn.)
E The 10-year-old reforestation

Figure 3.2 Reforestation land-use types



A Agricultural landscape in field
B The 6-year-old fallow land
C Orchard (*Litchi chinensis*)
D Corn field
E Rice field

Figure 3.3 Agricultural land-use types

3.2.2 Data collection

3.2.2.1 Aboveground vegetation carbon and plant community

To study the biomass, plots size of 50 x 50 m^2 were established in all land-use types. The number of plots chosen for each land-use type was based on its distribution in the study area and the expected variability in the amount of carbon. In the forest representing the most common type of evergreen and mixed deciduous forest was expected to have heterogeneous condition and high variability in the amount of carbon. Then, a larger number of plots (n = 8 for each site) were selected. For conservation and community forest and the reforestation, were expected to have quite homogeneous condition and lower variability in the amount of carbon, the fewer plots (n = 4 for each site) were chosen. For the agricultural land, selected plots contained in various fields. Fallow land and orchard covered with trees, plots of 50 x 50 m^2 were established (n = 4 for each site). Corn fields and paddy fields were established in plots size of 5 x 5 m^2 (n = 10 for each site) and sub-sampled in sub plot of 1x1 m^2.

All individual tree of ≥ 4.5 cm diameter at breast height (DBH) at 1.30 m in height above the ground were measured and identified. Saplings (trees less than 4.5 cm in DBH but taller than 1.30 m in height) were investigated with 25 sub plots of 4x4 m^2 and seeding (trees less than 4.5 cm in DBH and below 1.30 m in height) were investigated by 25 sub plots of 1 x 1 m^2 in each plot of 50 x 50 m^2 in the forest, the reforestation, and the fallow land. Density (individual ha^{-1}), basal area (m^2 ha^{-1}) and biomass (Mg ha^{-1}) were calculated. In each plot of 50 x 50 m^2, five sub plots of 4 x 4 m^2 were selected to harvest all saplings, ten sub plots of 1 x 1 m^2 were selected to harvest all seeding and understory layer (herbaceous and non-woody vegetations).

The vegetation in all sample plots was cut at aboveground position. The sapling and seedling samples were separated from stem, branch and leaves, while understory vegetations were separated into herbs and grasses. Fresh weight of each form of sapling, seeding and understory vegetation was measured and recorded. Sample from each component (at least 1,000 g for seedlings, 500g for sapling and 200g for understory vegetations) was taken to laboratory for oven-drying at 70 °C until get a constant weight. This final weight was used to determine the ratio of dry and fresh weight, which was applied to the entire of sample in order to convert to dry weight. The aboveground biomass of each plot was the sum of the aboveground dry mass of all individual trees, sapling, seeding and understory vegetation. All aboveground components were calculated to be equivalent to 50% of C content (Brown and Lugo, 1984, Levine *et al*., 1995).

To estimate the biomass of forest, reforestation and fallow land, the DBH and height of trees are estimated by SILVIC Program. The aboveground biomass was calculated using the developed allometric equations in Thailand (Appendix 1).

For *Litchi chinensis* biomass, ten sample trees were harvested according to the distribution of DBH class and stem form. After measuring DBH, the sample trees were cut and measured the total height and diameter at the lowest living branch, finally cut stem into logs at length from the bottom to 0.3 m., 1.0 m, 2.0, 3.0, to the top. Each part was measured the diameter after that separated and weighted living branch and leaves. Each sample was oven-dried at 80 °C to constant weight to determine the ratio of dry and fresh weight (water content). Allometric equations were formulated by linear regression analysis with log-transformed data of dry weight and DBH; and used to calculate lines of best fit. The *Litchi chinensis* equations were developed by this study as follows:

$Ws = 0.0267\ D^2H^{0.8712}$ $r^2 = 0.9941$

$Wb = 0.0170\ D^2H^{0.8023}$ $r^2 = 0.9895$

$Wl = 0.0030\ D^2H^{1.2113}$ $r^2 = 0.9858$ (equation 3.1)

To estimate the biomass of sapling, individuals were harvested and measured to fit biomass equation. The equations for sapling were developed at the forest site as follows:

Equation for sapling in evergreen forest

$Ws = 0.0928\ D^2H^{0.7653}$ $r^2 = 0.9754$

$Wl = 0.0105\ D^2H^{0.8245}$ $r^2 = 0.9320$

$Wb = 0.0214\ D^2H^{0.6416}$ $r^2 = 0.8839$ (equation 3.2)

Equation for sapling in Mixed deciduous forest

$Ws = 0.0813\ D^2H^{0.7365}$ $r^2 = 0.9862$

$Wl = 0.0074\ D^2H^{0.9236}$ $r^2 = 0.8458$

$Wb = 0.0162\ D^2H^{1.0353}$ $r^2 = 0.9037$ (equation 3.3)

Where D is the diameter at breast height (cm), H is the height of tree (m), Ws is the stem dry weight (kg), Wb is the branch dry weight (kg) and Wl is the leave dry weight (kg)

3.2.2.2 Aboveground litter carbon

Aboveground litter comprised litter standing (leaf, twigs and fine woody materials) and coarse woody debris (> 2 cm diameter). In each plot of 50 x 50 m^2, litter samples were collected in the nine sub plots of 1 x 1 m^2 and placed in paper bags. Aboveground litter was oven-dried at 55 °C to constant weight and sorted into litter classes. In each plot of 50 x 50 m^2, coarse woody debris was measured in one plot of 10 x 10 m^2. The material was weighted and sample of at least 10% of the total fresh weight in the plot was collected to estimate dry weight in the laboratory. The sub-samples were grounded to a fine powder using a grinding machine. Each of these was then weighted and rolled in tin cups for carbon analysis using dry combustion methods. Sum of carbon in each litter class was computed for stocks of aboveground litter carbon.

3.3 DATA ANALYSIS

The data analyses from all sampling plots were computerized and compared. Total density and basal area were calculated for every plot in units of stem ha^{-1} and m^2 ha^{-1} (summing up the basal area of each tree) and extrapolating to a hectare (Appendix 2).

To estimate the diversity of vegetation families, the Shannon – Wiener Index method (Shannon and Wiener, 1949) was commonly used (Appendix 2). The index was calculated from the proportion of number of individual families relative to the total number of families in the sample plots, and then multiplied by the natural logarithm of this proportion. The resulting product was summed across families, and multiplied by -1.

To analyze the vegetation characteristics, Importance Value Indices (IVI) were calculated for each families (Appendix 2) which taken into consideration in terms of the number of individuals (density) belonging to each families, their basal areas (dominance) and distribution (frequency) in the plot. IVI could be ranged between 0-300 and could be calculated as the following equation (Müller-Dombois and Ellenberg, 1974):

For biomass equation, SILVIC Program that was developed from the relationship between DBH and Ht by hyperbolic equation or D-H curve (Ogawa *et al*., 1961) was used to tree height estimation tree (Ht) by using a formerly minimum of 40 well selected trees in various sizes in the sample plot. Assuming that h equal one, the other coefficients, A and H* for each stand were calculated using the non-linear least square method, and their curves were drawn (Appendix 2).

3.4 STATISTICAL ANALYSIS

Differences in aboveground carbon, litter and coarse woody debris carbon in each land-use type and between land-use types were analyzed using a One-way Analysis of Variance (ANOVA; within treatment and between treatments). Post-hoc multiple comparison method was used to compare a difference between and within treatments.

3.5 RESULTS AND DISCUSSION

3.5.1 Structural variables, biomass and carbon sequestration

Average tree densities were observed in each land-use types (Table 3.2, Appendix 3). It found that average tree density was the highest in the conservation forest (805.75 ± 14.01 stem ha^{-1}), while the average tree density in the community forest was the lowest (209.00 ± 26.05 stem ha^{-1}). Generally, large trees (DBH > 25 cm) were found in the natural forest compared to the reforestation and fallow land. In natural forest, the low basal area and biomass of tree (DBH < 25 cm) was observed in natural hill evergreen forest, dry evergreen forest and mixed deciduous forest in this study. As the results, the comparison between this study and Kaeng Krachan National Park indicated the total tree density was 886.00 stem ha^{-1} in hill evergreen forest, 971.00 stem ha^{-1} in dry evergreen forest and 801.00 stem ha^{-1} in mixed deciduous forest (Jampanin, 2004), while the study in Huy Kha Khaeng Protected Area was 1,177.00 stem ha^{-1} in dry evergreen forest (Visaratana and Chernkhuntod, 2005).

In terms of community forest, normally it is an old forest either undisturbed condition or disturbed condition that is only allowed for community use under the community management based on the conservation concept. To compare with other managed forests in Thailand, the conservation and community forests in this study have the tree density (≥ 4.5 cm in DBH) to correspond with other types of managed forests in Thailand (Appendix 4).

In the reforestation, the tree density tended to decrease in comparison to age that indicated the 26-year-old reforestation to have the lowest density of 336.00 ± 27.82 stem ha^{-1} (Table 3.2). It is clear that the planting process of 26-year-old plot was clear cut before replanting the tree while the 10-year-old reforestation and 9-year-old reforestation were replanted and based on ecological restoration concept, so there are many native trees to be kept in the reforestation area. Many native trees were similar to the one found in mixed deciduous forest and conservation forest, but most of DBH size class were equal or smaller than 25 cm. It is clear that small trees (≤ 25 cm DBH) were dominant vegetation in the reforestation.

There was a general decreasing trend in total tree basal area with the conversion of the forest to the reforestation (Table 3.2). In the forest, total basal area ranged from 19.80 ± 2.77 to 34.59 ± 2.65 m^2 ha^{-1}, more than 65% of basal area was in large trees (DBH > 25 cm). Forest basal area in this study trends to correspond with other studies in particular to the study of Jampanin (2004) that indicated the basal area of hill evergreen forest, dry evergreen forest and mixed deciduous forest as 36.12 m^2 ha^{-1}, 16.75 m^2 ha^{-1} and 28.99 m^2 ha^{-1}, respectively. This indicated that natural forest in this study comprised large tree size classes. For managed forest, basal area in conservation forests showed the same pattern as density: similar to other managed forests, while community forest had high basal area. Particularly, it is notable that the basal area of trees was approximately double of other community forests (Appendix 4).

Table 3.2 Density, basal area and biomass of trees in different land-use types.

Land use type	Density (stem ha^{-1})			Basal area (m^{2} ha^{-1})			Biomass (Mg ha^{-1})		
	Dbh ≤25 cm	Dbh >25 cm	Total	Dbh ≤25 cm	Dbh >25 cm	Total	Dbh ≤25 cm	Dbh >25 cm	Total
HEF	441.50 ± 45.39 cd	150.50 ± 28.52 a	592.00 ± 36.27 bc	7.22 ± 1.74 abc	27.37 ± 3.78 a	34.59 ± 2.65 a	51.08 ± 12.29 a	238.52 ± 32.76 a	289.60 ± 24.76 a
DEF	392.75 ± 41.31 de	116.50 ± 19.29 ab	509.25 ± 41.15 c	4.72 ± 1.14 bc	27.18 ± 6.30 ab	31.90 ± 5.94 ab	32.49 ± 8.64 bc	235.83 ± 41.43 a	268.32 ± 38.17 a
MDF	638.50 ± 54.93 ab	118.50 ± 19.59 ab	757.00 ± 55.83 a	7.93 ± 1.05 a	15.11 ± 2.28 c	23.04 ± 1.98 c	42.34 ± 6.37 ab	108.62 ± 17.15 b	150.96 ± 14.80 b
CSF	700.75 ± 14.13 ab	105.00 ± 8.87 ab	805.75 ± 14.01 a	8.28 ± 0.90 ab	17.34 ± 1.53 bc	25.62 ± 1.07 bc	43.66 ± 6.70 ab	137.60 ± 5.33 b	181.26 ± 10.05 b
CMF	116.00 ± 18.40 g	93.00 ± 15.79 abcd	209.00 ± 26.05 e	1.79 ± 0.76 d	18.01 ± 3.23 abcde	19.80 ± 2.77 cd	10.10 ± 1.74 d	136.60 ± 18.11 b	146.70 ± 16.54 b
RF26	255.00 ± 26.76 f	81.00 ± 15.19 bcd	336.00 ± 27.82 de	6.55 ± 1.10 abc	5.63 ± 1.75 de	12.18 ± 2.10 de	34.63 ± 9.92 abc	37.12 ± 10.84 cdef	71.75 ± 13.88 cd
RF19	447.00 ± 38.10 cde	8.00 ± 1.82 cd	455.00 ± 38.06 cd	3.95 ± 0.75 cd	0.77 ± 0.28 de	4.72 ± 0.70 ef	18.48 ± 3.20 cd	5.46 ± 3.52 def	23.94 ± 3.28 c
RF14	553.00 ± 29.74 bc	11.00 ± 1.41 c	564.00 ± 43.73 bc	7.47 ± 0.99 abc	0.70 ± 0.26 de	8.17 ± 0.81 ef	39.38 ± 7.69 abc	4.13 ± 0.58 de	43.51 ± 7.76 cd
RF10	700.00 ± 51.25 ab	30.00 ± 7.30 cd	730.00 ± 44.15 ab	7.30 ± 2.40 abcd	3.53 ± 0.80 de	10.84 ± 2.59 def	40.97 ± 8.25 abc	26.43 ± 3.59 c	67.40 ± 10.87 cd
RF9	760.00 ± 40.03 a	2.00 ± 1.82 d	762.00 ± 41.32 a	5.05 ± 1.00 abcd	0.13 ± 0.05 e	5.18 ± 1.01 ef	20.69 ± 3.77 bcd	0.85 ± 0.46 f	21.54 ± 3.92 cd
FL	285.00 ± 13.61 ef	3.00 ± 2.00 cd	288.00 ± 11.78 e	1.08 ± 0.47 d	0.91 ± 0.10 d	1.99 ± 0.54 f	4.27 ± 2.21 d	6.16 ± 0.95 e	10.43 ± 2.75 d

Table 3.3 Density, basal area and biomass of trees in the reforestation.

Land use type	Density (stem ha^{-1})			Basal area (m^{2} ha^{-1})			Biomass (Mg ha^{-1})		
	Dbh ≤25 cm	Dbh >25 cm	Total	Dbh ≤25 cm	Dbh >25 cm	Total	Dbh ≤25 cm	Dbh >25 cm	Total
RF26	156.00 ± 39.60 b	45.00 ± 20.75 a	201.00 ± 39.65 b	4.46 ± 0.74 a	2.68 ± 1.31 a	7.14 ± 1.71 a	21.29 ± 7.14 abc	13.09 ± 5.98 a	34.38 ± 5.91 a
RF19	70.00 ± 20.78 bc	8.00 ± 4.61 a	78.00 ± 25.40 c	1.07 ± 0.27 b	0.77 ± 0.49 a	1.84 ± 0.75 bc	5.66 ± 1.39 b	5.46 ± 2.12 ab	11.12 ± 3.12 bc
RF14	455.00 ± 32.35 a	9.00 ± 8.81 a	464.00 ± 34.13 a	7.04 ± 0.94 a	0.53 ± 0.26 a	7.57 ± 1.02 a	37.82 ± 7.45 a	2.93 ± 1.88 b	40.75 ± 6.48 a
RF10	73.00 ± 19.42 bc	0.00 ± 0.00	73.00 ± 19.42 c	0.71 ± 0.17 b	0.00 ± 0.00	0.71 ± 0.17 b	3.88 ± 0.92 b	0.00 ± 0.00	3.88 ± 0.92 cd
RF9	7.00 ± 2.16 c	0.00 ± 0.00	7.00 ± 2.16 c	0.03 ± 0.03 c	0.00 ± 0.00	0.03 ± 0.01 c	0.19 ± 0.07 c	0.00 ± 0.00	0.19 ± 0.07 d

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

In the reforestation, total basal area ranged from 4.72 ± 0.70 to 12.18 ± 2.10 m^2 ha^{-1}, large proportion of basal area (more than 53%) was found in small trees (DBH ≤ 25 cm). Tree density and basal area in the reforestation varied in this study. It depended on available spacing of plantation and survival rate. Plantation at wider spacing had lower individual density than those at closer (Sumuntakul and Viriyabuncha, 2007). Especially, in *Tectona grandis,* the spacing of trees and the number, timing and intensity of thinnings strongly affected the pattern of growth and the yield of the plantation (Krishnapillay, 2000). Comparisons of tree plantation in the reforestation, tree plantation density of the 14-year-old reforestation (464.00 ± 34.13 stem ha^{-1}) was significantly greater than that in other reforestations ($P < 0.05$). The tree plantation density in the 9-year old reforestation was the lowest (7.00 ± 2.16 stem ha^{-1}). Similarly, plantation basal area was the greatest in the 14-year-old reforestation (7.57 ± 1.02 m^2 ha^{-1}), while the plantation basal area in the 9-year-old reforestation was the lowest (0.03 ± 0.01 m^2 ha^{-1}). Moreover, the growth and survivorship of tree in plantation varied with the planted species and site conditions in the open area. Growth rates may have been showed due to factors such as competition from weeds and grasses, low nutrient availability, or drought stress in ecosystem (Silver *et al*., 2004).

Total tree biomass tended to increase within the forest and to be lower in the reforestation (Table 3.2). Total tree biomass was the greatest in the hill evergreen forest (289.60 ± 24.76 Mg ha^{-1}), while total tree biomass in the 6-year-old fallow land was the lowest (10.43 ± 2.75 Mg ha^{-1}) ($P < 0.05$). In the forest, the most tree biomass accumulation was found in trees > 25 cm DBH, accounted for 93.11% in community forest, 87.89% in dry evergreen forest, 82.3% in hill evergreen forest, 75.91% in conservation forest and 71.95% in natural mixed deciduous forest. Total tree biomass in the community forest was lower than other forests, although it was not significantly different from natural mixed deciduous and conservation forest. According to the results of the study, the aboveground carbon storage of trees in the forests corresponds to the range of other forests in Thailand (Appendix 5). When compared to the studies in neighboring countries, these results were fairly similar to the natural forests in Malaysia, the Philippines and Indonesia. The results suggest that a large proportion of the net accumulation of aboveground biomass in tropical forests occurs as continued growth of large trees as opposed to ingrowths of smaller individuals (Lugo and Brown, 1992).

While in the reforestation, the most tree biomass accumulation was found in trees ≤ 25 cm DBH, accounted for 96.01% in the 9-year-old reforestation, 90.51% in the 14-year-old reforestation, 77.19% in the 19-year-old reforestation, 60.79% in the 10-year-old reforestation and 48.26% in the 26-year-old reforestation, respectively. Although the total tree biomass of the 10-year-old reforestation was quite high, most tree biomass was found in remained old native trees in this area. The carbon accumulation in reforestation (10.77-35.62 Mg C ha^{-1}) demonstrated relatively low carbon storage within the range for forest plantations in Thailand (Appendix 6). Most of plantation in Thailand was estimated in units of Forest Industry Organization which technically managed tree plantations as a renewable resource for producing timber and pulp. But plantation at research sites were planted to restore the forest ecosystem, they grow up by themselves under the natural condition through natural regeneration. Generally, species selected in plantation was inhibited by intense competition associated with vigorous growth of tree species in natural forest (Kamo *et al*., 2002). Many native species of tree in natural forest can become widely established in these reforestation sites. Plantations of exotic species in research sites have shown that more native species grew up among stands of plantation. The biomass of native species accumulated approximately the same amount of planted species in the 19- and 26-year-old reforestation. On the other hand, plantation of single native species in the 14-year-old reforestation, most of biomass accumulated in planted species. It must be noted that the carbon storage of the reforestation depends on the competition and survival of planted species and/or native species in that area.

Generally, the number of seedling was higher proportion than saplings and trees in all land-use types (Figure 3.4, Appendix 7). With increasing forest age and development, the biomass of sapling (<4.5 cm in DBH but taller than 1.30 m in height), seedling (<4.5 cm in DBH and below 1.30 m in height) and understory layer (annual plants and herbs) declined and became a very small proportion of the total vegetation biomass (Table 3.4). In the forest, the density of sapling and seedling in hill evergreen forest, dry evergreen forest, mixed deciduous forest and conservation forest were higher than those in the community forest ($P < 0.05$). Minor disturbances associated with the utilization of community forest, resulted in lower proportions of small sapling and seedling. To compare with other studies, the density of saplings and seedling in the forest in this study were similar to density of sapling and seedlings in

Nam Ki sub-watershed, Nan (S. P. S. Consulting Service Ltd., 1997). However, Visaratana and Chernkhuntod (2004) reported higher saplings and seedlings density observed in dry evergreen forest at Phuluang National Forest Reserves, Nakhon Ratchasima.

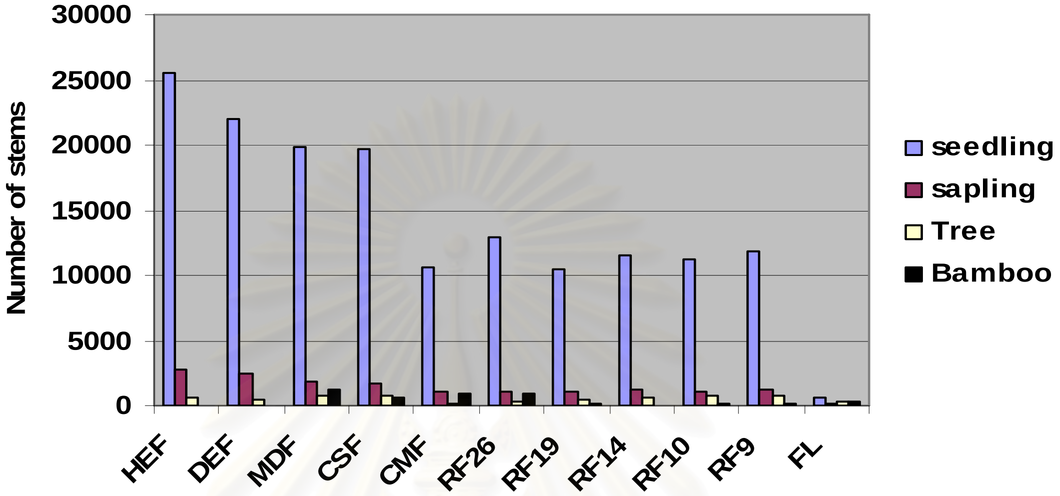


Figure 3.4 Structural composition of tree, sapling, seedling and bamboo (stem per hectare)

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

Biomass of sapling in the forest ranged from 2.68 ± 0.52 Mg ha^{-1} to 6.53 ± 0.18 Mg ha^{-1}, represented 1.73% to 2.18% of total vegetation biomass. The proportion of sapling biomass represented a small fraction comparing to tree biomass in natural forests, similarly with the proportion of sapling biomass in dry evergreen forest (2.12% by Visaratana and Chernkhuntod, 2004). In the reforestation, biomass of sapling ranged from 2.42 ± 0.33 Mg ha^{-1} to 3.64 ± 0.80 Mg ha^{-1}, represented 3.31% to 11.63% of total vegetation biomass. The decreasing trend was observed in the 26-year-old reforestation and the 10-year-old reforestation which had high proportion of large trees in that area. However, the proportion of sapling and seedlings biomass in the reforestation was higher than those in the forest in this study. This means that the reforestation process was clearly in an early stage of secondary succession (Table 3.4).

The biomass of seedling ranged from 2.25 ± 0.08 Mg ha^{-1} to 3.77 ± 0.19 Mg ha^{-1} in the forests and ranged from 2.26 ± 0.08 Mg ha^{-1} to 2.50 ± 0.09 Mg ha^{-1} in the reforestation. The proportion of seedling biomass to total vegetation biomass was greater (ranged from 3.07% to 8.19%) in the reforestation compared to the forest (ranged from 1.45% to 1.77%) (Table 3.4). However, the proportion of sapling and seedlings biomass in the reforestation was higher than those in the forest. This means that the reforestation was also in an early stage of secondary succession.

The biomass of understory layer accounted for less than 1 Mg ha^{-1} in all land-use types. In the forest and the reforestation, the proportion of understory biomass to total vegetation biomass was less than 0.62%, excepting the proportion was 1.02% in the 19-year-old reforestation, because biomass of the 19-year-old reforestation decreased with the reduction in survival rate of tree plantation. As a result, understory layer growth increased in abandonment area.

The biomass of bamboo was the highest in natural mixed deciduous forest (9.05 ± 0.45 Mg ha^{-1}), represented 5.43% of total vegetation biomass. As the forest degraded, the number of bamboo increased in the mixed deciduous forest and community forest. The biomass of bamboo in the 14-year-old reforestation was the lowest (0.20 ± 0.02 Mg ha^{-1}), represented only 0.40% of total vegetation biomass. Because tree plantation had a high density, it was influencing a low space-gap and a poor distribution of bamboo in this area. Moreover, bamboo was completely absent in both hill evergreen forest and dry evergreen forest.

As the results, the differences were observed between the forest and the reforestation with respect to total vegetation biomass (Table 3.4). In the forest, total vegetation biomass was the greatest in hill evergreen forest (300.14 ± 25.16 Mg ha^{-1}) while total vegetation biomass in community forest was the lowest (157.27 ± 17.08 Mg ha^{-1}). The total biomass in conservation forest was as high as 190.35 ± 10.31 Mg ha^{-1} because this area was in water source, high density and basal area of tree. In the reforestation, total vegetation biomass was the greatest in the 26-year-old reforestation (81.40 ± 12.73 Mg ha^{-1}). Generally, total vegetation biomass was found high accumulation in old reforestation due to the well-growing of single species tree in plantation. These impacts were clearly found in the 26-year-old and 14-year-old reforestation.

Table 3.4 Total biomass in different land-use types (Mg ha^{-1})

Land use type	Tree	% of total	Sapling	% of total	Seedling	% of total	Understory	% of total	Bamboo	% of total	Total	% of total
HEF	289.60 ± 25.24 a	96.49	6.53 ± 0.18 a	2.18	3.77 ± 0.19 a	1.25	0.23 ± 0.04 bc	0.08	-	-	300.14 ± 25.16 a	100.00
DEF	268.32 ± 27.28 ab	96.60	5.88 ± 0.37 a	2.12	3.36 ± 0.22 a	1.21	0.20 ± 0.01 c	0.07	-	-	277.77 ± 26.78 a	100.00
MDF	150.96 ± 14.55 c	90.61	3.36 ± 0.89 abc	2.01	2.95 ± 0.14 b	1.77	0.30 ± 0.02 b	0.18	9.05 ± 0.45 a	5.43	166.61 ± 15.29 b	100.00
CSF	181.26 ± 10.05 bc	95.23	3.54 ± 0.47 b	1.86	2.89 ± 0.13 bc	1.52	0.18 ± 0.02 c	0.09	2.47 ± 0.41 bc	1.30	190.35 ± 10.31 b	100.00
CMF	144.14 ± 46.92 abcde	93.17	2.68 ± 0.52 bc	1.73	2.25 ± 0.08 d	1.45	0.15 ± 0.01 c	0.10	5.49 ± 0.94 ab	3.55	157.27 ± 17.08 b	100.00
RF26	71.75 ± 13.88 de	88.14	2.94 ± 0.40 b	3.62	2.50 ± 0.09 cd	3.07	0.18 ± 0.03 c	0.22	4.03 ± 1.08 bcd	4.95	81.40 ± 12.73 c	100.00
RF19	23.94 ± 3.28 d	76.29	3.49 ± 0.77 abc	11.15	2.26 ± 0.08 d	7.23	0.32 ± 0.02 b	1.02	1.36 ± 0.28 bcd	4.33	31.38 ± 3.27 de	100.00
RF14	43.51 ± 5.01 de	87.18	3.64 ± 0.80 abc	11.63	2.33 ± 0.12 d	4.67	0.22 ± 0.02 c	0.44	0.20 ± 0.02 bcd	0.40	49.91 ± 5.28 cd	100.00
RF10	67.40 ± 14.91 de	92.20	2.42 ± 0.33 b	3.31	2.31 ± 0.12 d	3.16	0.15 ± 0.01 c	0.20	0.82 ± 0.68 cd	1.12	73.10 ± 14.60 cd	100.00
RF9	21.54 ± 3.77 de	75.37	3.38 ± 0.46 b	11.48	2.34 ± 0.07 d	8.19	0.18 ± 0.03 c	0.62	1.14 ± 0.31 cd	3.99	28.58 ± 3.96 de	100.00
FL	10.42 ± 2.24 e	88.13	0.10 ± 0.05 c	0.87	0.09 ± 0.03 e	0.77	0.75 ± 0.07 a	6.33	0.46 ± 0.19 d	3.90	11.82 ± 2.43 e	100.00

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

The 6-year-old fallow land tended to have significant difference as the lowest total density of 288.00 ± 11.78 stem ha^{-1}, basal area of 1.98 ± 0.72 m^{2} ha^{-1} (Table 3.2) and vegetation biomass of 11.82 ± 2.43 Mg ha^{-1} (Table 3.4) at $P < 0.05$. Ruankaew (2004) reported higher density and basal area (2,450 stem ha^{-1}, 10.30 m^{2} ha^{-1} and 1,000 stem ha^{-1}, 15.10 m^{2} ha^{-1} in Khun Mae Yot and Mae Hae Tai, respectively in Mae Cham, Chiang Mai) of trees in 6-year-old fallow of swidden systems than those in this study. With the ethnic groups practiced traditional techniques in swidden systems, they normally kept large trees in a field during the process of clearing and preparing land. These left-over trees are growing and possible provide the new recruitment during early years of secondary succession. Woody plants re-sprouting from roots and tree stumps can emerge and gradually suppress the weeds (Schmidt-Vogt, 2001). Moreover, the low density, basal area, and diversity observed in the 6-year-old fallow, which were the result of intensive cultivation over several years.

The tree biomass of 6-year-old fallow land was the lowest at 10.43 ± 4.24 Mg ha^{-1} which had significantly different from other agricultural land use at $P < 0.05$. Most of tree biomass accumulation in the 6-year-old fallow land (69.61%) was found in tree > 25 cm DBH that were left standing by farmers in this area. Reasonably, the development of a woody fallow depends on the availability of stumps and rootstocks. Also, crucial is the availability of stumps and roots left in the fields, from which coppice shoots and root suckers can develop (Schmidt-Vogt, 2001).

The biomass of sapling and seedlings in the 6-year-old fallow land were the lowest at 0.10 ± 0.05 Mg ha^{-1} and 0.09 ± 0.03 Mg ha^{-1}, respectively, which had significantly different at $P < 0.05$. They were accounted for 0.87% and 0.76% of total biomass (Table 3.4). The biomass of understory layer in the 6-year-old fallow land (0.75 ± 0.07 Mg ha^{-1}) was significantly greater than other land-use types ($P < 0.05$) (Table 3.4). Although the lowest sapling and seedling biomass observed in the 6-year-old fallow land, the highest understory biomass also contained in this area. In intensive cultivation, the number of re-sprouting plant decline because of the lower probability of seed generation. In the study site, grasses and perennial herbs such as *Imperata cylindrica* and *Chromolaena odorata* were found and dominated in some area. Grasses and herbs might be the result of the high understory biomass in this case.

Comparison to other land-use types in agricultural land, the amount of aboveground carbon in the 6-year-old fallow land and fruit tree plantation (*Litchi chinensis*) were similar. Trees stored more than 97.25% of total aboveground carbon in both sites, while 100.00% of total aboveground carbon in rice and corn fields were stored in crop cultivation. Like as forests, fallow and orchard trees can store carbon in several years but they are occasionally clearing due to cultivate crop and/or change tree varieties in rotational system. Among all land-use types, fallow land and fruit orchards seem to have a minor role in sequestrating aboveground carbon particularly in trees. Generally, the characteristics of secondary forests and fallow recovery processes depend upon a variety of factors, such as land use history and competing forest uses and extraction (Ramakrishnan and Kushwaha, 2001). Moreover, many factors represented the relative effects of accumulated carbon in the reforestation and fallow land *i.e.* selected species in plantation, native species and size class of old native trees which remained in that area.

In all land-use types, there was a general decreasing trend in total vegetation biomass with the conversion of the forest to the reforestation and the fallow land (Table 3.4). The study found that tree biomass was the highest proportion of total vegetation biomass (more than 75.37%), except in rice and corn fields. All of total aboveground C in these agricultural fields was in crop cultivation. In the forest and the reforestation, biomass of saplings was greater than biomass of seedlings and understory layer, while biomass of understory layer was greater than saplings and seedlings in the 6-year-old fallow land. Biomass of bamboo in all land-use types was less than 5.43% of total vegetation biomass.

3.5.2 Tree community and tree diversity

Tree families in the forest, reforestation and fallow land were shown in Appendix 8 and 9. In the reforestation, the 10-year-old reforestation had the highest diversity, 25 families were found (Table 3.5). This was effected by the policy and planning of the Royal Forest Department that was emphasized on the restoration of ecosystem structure and function. Therefore, the old native species have been conserved and the native species also replanted. Regarding the intermediate disturbance hypothesis states, species richness is highest at an intermediate level of disturbance with respect to both frequency and intensity (Connell, 1978). In terms of indices, the 19-year-old and 10-year-old reforestation have closely reached the level equivalent to that of the forest, while the 6-year-old fallow land has reached the same level of diversity as the 26-year-old and 14-year-old reforestation. Regarding the single species plantation pattern, both reforestations cause decreasing in diversity. The mixed species plantation resulted in a large increase in diversity, even though the original planting was a little number of common families. Plantations of single tree species are often considered to be associated with the lowest biological diversity comparing to natural forest ecosystems (Kamo *et al*., 2002). It is clear that the mixed native species plantations (the 9- and 10-year-old reforestations) contained more diversity than the single exotic species plantations (the 14- and 26-year-old reforestation). These facts imply that the mixed native species plantations at the study site could facilitate the establishment of various plant species, and consequently promote secondary succession. In the 19-year-old reforestation, two species of *Eucalyptus camaldulensis* Dehn. (Eucalyptus) and *Tectona grandis* Linn. (Teak) were planted, but T. *grandis* had a low survival rate. There were only five individuals found (300 trees ha^{-1} of T. *grandis* and 300 trees ha^{-1} of E. *camaldulensis* were planted) at research sites. While E. *camaldulensis* (non-native species) had a high relative frequency, dominance and abundance, it successfully establish widely after planted. It is noteworthy that many plant species became invaded in the *E. camaldulensis* stand. Although eucalyptus are often considered to have very few plant species growing on their forest floor, which is a cause for concern in eucalyptus plantations (Kamo *et al*., 2002).

In fallow land, Ruankaew (2004) reported higher diversity of trees in 6-year-old fallow of swidden systems (23 families and 11 families in Khun Mae Yot and Mae Hae Tai, respectively in Mae Cham, Chiang Mai) than those in this study.

In case of tree diversity, it was identified by Shannon-Wiener’s index, Simpson’s index and Pielou’s evenness index in order to compare the diversity of different land-use types (Table 3.5). Land-use change resulted in a big change in diversity, species diversity indices of tree in natural forest ranged from 2.09 to 2.81, which tended to be greater than that in other land-use types. The Shanon-Wiener’s index, Simpson’s index of diversity and Pielou’s evenness index were the highest in hill evergreen forest and followed by mixed deciduous forest in Table 3.5. While the tree diversity indices in the 14-year-old were the lowest as of 0.74 and 0.32; and the both indices of 26-year-old reforestations were1.00 and 0.61, respectively. In term of tree diversity, managed forest in this study was similar to other studies (Appendix 4). As the results, the values of Shannon-Wiener's index appeared to be corresponding to the values of Simpson's index in all land-use types. Nevertheless, the Pielou's evenness index also reflected the evenness of species distribution, which indicated the forest had highest evenness of species distribution. While the 14-year-old reforestations had lowest value as of 0.38 and followed by the 26-year-old reforestation as of 0.58. It is quite clear that natural/protected forests are usually more effective repositories of plant diversity than forests under management for extractive use (Bruner *et al*., 2001). Nevertheless, community forest is a significant and vital repository of biodiversity values alongside the protected area system.

Table 3.5 Vegetation composition and structural data of vegetation

Land –use type	Number of tree families	Shannon-Wiener's index	Simpson's index	Pielou's evenness index
HEF	31	2.81	0.91	0.88
DEF	26	2.34	0.85	0.79
MDF	28	2.43	0.88	0.87
CSF	25	2.14	0.84	0.72
CMF	21	2.09	0.82	0.83
RF26	9	1.00	0.61	0.58
RF19	22	2.25	0.86	0.85
RF14	12	0.74	0.32	0.38
RF10	25	2.17	0.87	0.81
RF9	24	1.75	0.72	0.67
FL	10	1.08	0.50	0.56

The importance value index (IVI) is more than 10.00 % in different land-use types shown in Table 3.6 and 3.7. The dominant of tree families in hill evergreen forest, like other hill evergreen forests in Northern Thailand, was Fagaceae that represented with the greatest IVI (45.77%). While Datisceae was the dominant familiy in dry evergreen, it presented with the greatest IVI (36.28%). There was different dominant family in mixed deciduous forest, Papilionoideae was the dominant family in natural mixed deciduous forest and conservation forest, it presented with high IVI (57.90% and 83.69% in natural mixed deciduous and conservation forest, respectively). Foe community forest, Euphorbiaceae was the dominant family with the greatest IVI (95.93%). Only 3-codominant families found in mixed deciduous forest including conservation and community forest.

Table 3.6 Tree families with importance index more than 10.00 % in forest

Families	Importance value index (%)				
	HEF	DEF	MDF	CSF	CMF
Anacardiceae			14.08	12.48	
Annonaceae	33.11				
Apocynaceae	10.17				
Bignoniaceae			11.27	15.80	14.48
Burseraceae		13.36			
Caesalpilionoideae			24.75		
Combretaceae				14.07	
Datiscaceae		36.28			
Dipterocarpaceae	17.86	18.25			
Euphorbiaceae	14.13	26.72		23.27	95.93
Fagaceae	45.77	12.04			
Guttiferae				12.28	11.99
Labiatae			12.34		
Lauraceae	15.79				
Lythraceae			19.06		
Meliaceae	14.83	20.34			
Mimosoideae			10.74		
Moraceae	24.87	12.72	11.99		
Myrtaceae	19.35				
Papilionoideae			57.90	83.69	
Rosaceae					10.27
Rubiaceae		17.14			
Sapindaceae			44.35	13.69	36.03
Simaroubaceae			15.43	62.04	35.97
2Sonneratiaceae		22.12			
Symplocaceae					11.86

In the reforestation, the 26-year-old, 19-year-old and 14 year-old reforestation, families plantation had an influence on dominant family. Labiatae family (*Gmelina* *aborea* Roxb. and *Tectona grandis* Linn.), the planted family was presented with the greatest IVI (137.85% and 188.45%) in the 26-year-old and 14-year-old reforestation and both composed similar 3 co-dominant families. The 19-year-old reforestation is dominated by Myrtaceae family (*Eucalyptus camaldulensis* Dehn.), the planted family was presented with the greatest IVI (63.97%). In the 10-year-old and 9-year-old reforestation, the families dominant (Cryteroniaceae and Sapindaceae families) were original families in degraded forests. In the 6-year-old fallow land, Euphorbiaceae family, regenerated family shown the greatest IVI (100.28%), corresponded with its high number of stems. Another Irvigiaceae and Labiatae families were residual original families, as shown high IVI (table 3.7).

Table 3.7 Tree families with importance index more than 10.00 % in reforestation and fallow land

Families	Importance value index (%)					
	RF26	RF19	RF14	RF10	RF9	FL
Anacardiceae	10.84	24.72	11.30			
Annonaceae						
Apocynaceae						
Bignoniaceae	13.07		13.08		10.80	19.76
Burseraceae			16.51		10.94	
Caesalpilionoideae				15.03		31.89
Cryteroniaceae		21.19		40.71	26.97	
Dilleniaceae	13.36					
Ebenceae	11.21					
Euphorbiaceae	11.48		13.21	28.95		100.28
Guttiferae		34.84		27.45	35.15	
Irvigiaceae	11.75					48.03
Labiatae	137.85		188.45		14.74	45.53
Lauraceae						12.56
Meliaceae				11.49		
Moraceae		14.86		31.35	11.99	
Myrtaceae		63.97				
Papilionoideae	85.15	14.91	22.43			
Rubiaceae						
Sapindaceae		33.37		27.77	95.96	
Simaroubaceae		14.02		12.20		
Symplocaceae			11.46		30.65	23.38

3.5.3 Aboveground litter mass and carbon

Total aboveground litter mass and carbon varied significantly over land-use type ($P < 0.05$) (Table 3.8). Generally, litter mass and carbon were larger than woody debris mass and carbon in all land-use types. Total litter mass and carbon decreased in reforestation and fallow land. In the forest, litter mass and carbon ranged from 4.36 ± 0.12 to 9.51 ± 0.42 Mg ha^{-1} and from 1.98 ± 0.02 to 4.20 ± 0.05 Mg C ha^{-1}, respectively, while woody debris mass and carbon ranged from 3.35 ± 0.24 to 7.24 ± 0.44 Mg ha^{-1} and 1.50 ± 0.11 to 3.70 ± 0.21 Mg C ha^{-1}, respectively. In the reforestation, litter mass and carbon ranged from 1.68 ± 0.14 to 5.39 ± 0.33 Mg ha^{-1} and from 0.74 ± 0.02 to 2.41 ± 0.03 Mg C ha^{-1}, respectively, while woody debris mass and carbon ranged from 0.89 ± 0.08 to 1.98 ± 0.18 Mg ha^{-1} and from 0.39 ± 0.02 to 0.88 ± 0.08 Mg C ha^{-1}, respectively. Total aboveground litter mass and carbon in the 14-year-old reforestation was the highest because of high fine litter mass. Although fine litter mass and carbon in the 14-year-old reforestation was higher than that in natural and managed forest, woody debris mass and carbon in this reforestation became vice versa. Finally, it made total litter mass and carbon in the natural and managed forest higher than that in the 14-year-old reforestation ($P < 0.05$).

Aboveground litter mass in the forests was similar to the range of other forests (Appendix 10). In this study, litter represented 2.29-3.42% of total aboveground biomass for the forest and 4.20-10.80% of total aboveground biomass for the reforestation. This is a very low values compared to the 31% found by Dias *et al.* (2006) for coastal open woodland in Brazil but it corresponds to the 6-9% found by Barbosa and Fernside (2005) for Amazonian savannas, to the 3% found by Chen *et al.* (2003) for a tropical Australian savanna, and to the 2% and 11% found by Sierra *et al.* (2007) for a tropical primary and secondary forests in Colombia. The high litter stock in relation to living biomass caused by slow decomposition due to both low litter quality and harsh environmental conditions (Dias *et al.*, 2006), which may have an important role for carbon accumulation on this ecosystem. The data shows that litter decomposition of the forest is more active than that in the reforestation. Generally, many factors such as stand age and density, basal area, leaf area index and soil temperature are the factors influencing litter dynamics and production in forests (Yang *et al.*, 2005). In the reforestation, the litter quality varies with the age of the plantation and the species (Palm *et al*., 2001). However, the main perturbations in the litter system introduced by the plantation of native trees are not long lasting and these secondary forests have a high recovery capacity by decomposition of organic matter and emergence of forest undergrowth (Goma-Tchimbakala and Bernhard-Reversat, 2006). Many studies in tropical tree plantations showed a large accumulation of litter standing crop, especially when the planted species was exotic suggesting that local decomposers were adapted to the biochemical composition of the litter (Bernhard-Revarsat and Loumeto, 2002.) Therefore, plant diversity impacts on litter decomposition could occur through litter mixing effects and/or microclimate effects (Knops *et al*., 2001). Moreover, litterfall and turnover in forest ecosystems showed large temporal variations due to environmental factors such as temperature, rainfall and wind (Seneviratne, 2002).

A few studies of carbon in coarse woody debris, the estimated coarse woody debris mass in the forest and the reforestation in this study corresponded to the mean mass of primary forest (6.10 Mg ha^{-1}) and secondary forest (2.00 Mg ha^{-1}) in Colombia (Sierra *et al*., 2007). The higher aboveground litter carbon stocks in this study might imply that the forest floor was an important carbon pool in the forest ecosystem. However, the carbon pool on the forest floor was neglected in many studies (Sun *et al*., 2003, Guo *et al*., 2004 cited in Yang *et al*., 2005).

Table 3.8 Total mass and carbon of aboveground litter in different land-use types.

Land-use type	Mass (Mg ha^{-1})		C litter (Mg C ha^{-1})		Total litter mass (Mg ha^{-1})	Total litter C (Mg C ha^{-1})
	litter	Coarse woody debris	Fine litter	Coarse litter		
HEF	8.07 ± 0.38 a	7.01 ± 0.35 b	3.69 ± 0.03 b	3.17 ± 0.17 b	15.08 ± 0.50 b	6.86 ± 0.18 b
DEF	9.51 ± 0.42 b	7.24 ± 0.44 a	4.20 ± 0.05 a	3.70 ± 0.21 a	16.75 ± 0.60 a	7.90 ± 0.22 a
MDF	4.72 ± 0.37 e	3.42 ± 0.27 d	2.16 ± 0.02 e	1.54 ± 0.11 c	8.15 ± 0.43 d	3.69 ± 0.11 c
CSF	4.36 ± 0.12 f	3.58 ± 0.27 c	1.98 ± 0.02 f	1.59 ± 0.14 c	7.94 ± 0.31 e	3.57 ± 0.14 d
CMF	4.84 ± 0.31 d	3.35 ± 0.24 d	2.18 ± 0.03 d	1.50 ± 0.11 c	8.19 ± 0.37 c	3.68 ± 0.12 c
RF26	3.42 ± 0.11 h	1.75 ± 0.16 f	1.46 ± 0.03 h	0.76 ± 0.10 e	5.17 ± 0.19 h	2.23 ± 0.10 g
RF19	2.36 ± 0.15 i	1.15 ± 0.12 h	0.99 ± 0.02 i	0.51 ± 0.06 g	3.52 ± 0.21 i	1.50 ± 0.07 h
RF14	5.39 ± 0.33 c	1.53 ± 0.16 g	2.41 ± 0.03 c	0.68 ± 0.06 f	6.92 ± 0.40 f	3.10 ± 0.07 e
RF10	3.91 ± 0.26 g	1.98 ± 0.18 e	1.73 ± 0.02 g	0.88 ± 0.08 d	5.89 ± 0.34 g	2.61 ± 0.09 f
RF9	1.68 ± 0.14 j	0.89 ± 0.08 i	0.74 ± 0.02 j	0.39 ± 0.02 h	2.57 ± 0.17 j	1.13 ± 0.03 i
FL	0.26 ± 0.04 k	0.10 ± 0.02 j	0.10 ± 0.01 k	0.05 ± 0.01 i	0.36 ± 0.04 k	0.15 ± 0.01 j

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old).

3.5.4 Total aboveground carbon

Total aboveground carbon (TAGC) in different land-use types are shown in Table 3.9. TAGC was greater in the forest than the reforestation and the agricultural land. Overall, TAGC dominated by aboveground vegetation carbon while litter carbon was a small fraction of TAGC. Aboveground vegetation carbon represented more than 91.27% of TAGC in all land-use types, except that aboveground vegetation carbon in the 14-year-old reforestation represented as 88.95% of TAGC. In the forest, TAGC ranged from 82.31 ±8.49 to 156.93 ± 12.51 Mg C ha^{-1}, especially, TAGC in hill evergreen forest was greater than that in other forests. In the reforestation, TAGC ranged from 15.42 ± 1.97 to 42.93 ± 6.35 Mg C ha^{-1}, the TAGC of the 26-year-old reforestation was the greatest, even it was not significant. In the agricultural land, TAGC in the fruit tree plantation (*Litchi chinensis* Sonn. spp.) was the greatest (8.17 ± 0.75 Mg C ha^{-1}) while the lowest TAGC (2.49 ± 0.13 Mg C ha^{-1}) was estimated in the rice paddy field.

Table 3.9 Total aboveground carbon in different land-use types

Land-use type	Aboveground Vegetation carbon	% of total	Aboveground litter carbon	% of total	Total Aboveground carbon	%of total
HEF	150.07 ± 12.58 a	95.63	6.86 ± 0.18 b	4.37	156.93 ± 12.51 a	100.00
DEF	138.88 ± 13.39 ab	94.62	7.90 ± 0.22 a	5.38	146.79 ± 13.42 ab	100.00
MDF	83.31 ± 7.64 bc	95.76	3.69 ± 0.11 c	4.24	87.00 ± 7.67 bc	100.00
CSF	95.17 ± 5.15 abc	96.38	3.57 ± 0.14 d	3.62	98.74 ± 5.12 bc	100.00
CMF	78.63 ± 8.54 c	95.46	3.68 ± 0.12 c	4.54	82.31 ± 8.49 c	100.00
RF26	40.70 ± 6.37 defg	94.81	2.23 ± 0.10 g	5.19	42.93 ± 6.35 defg	100.00
RF19	15.69 ± 1.64 e	91.27	1.50 ± 0.07 h	8.73	17.19 ± 1.63 de	100.00
RF14	24.96 ± 2.64 de	88.95	3.10 ± 0.07 e	11.05	28.05 ± 2.62 d	100.00
RF10	36.55 ± 7.30 defg	93.34	2.61 ± 0.09 f	6.66	39.17 ± 7.34 defg	100.00
RF9	14.29 ± 1.98 efg	92.67	1.13 ± 0.03 i	7.33	15.41 ± 1.97 ef	100.00
FL	5.91 ± 1.21 ghi	97.52	0.15 ± 0.01 j	2.48	6.07 ± 1.22 gh	100.00
Litchi	8.15 ± 0.75 fghi	99.76	0.02 ± 0.01 k	0.24	8.17 ± 0.75 fgh	100.00
Rice	2.49 ± 0.11 i	100.00	0.00 ± 0.00 l	0.00	2.49 ± 0.11 h	100.00
Corn1	4.82 ± 0.46 h	100.00	0.00 ± 0.00 l	0.00	4.82 ± 0.46 fg	100.00
Corn2	4.96 ± 0.33 h	100.00	0.00 ± 0.00 l	0.00	4.96 ± 0.34 fg	100.00

3.6 CONCLUSION

In the forest and the reforestation, most of aboveground vegetation carbon was sequestered in trees. In the forest, the proportion of tree > 25 cm DBH increased and dominated in terms of basal area and biomass, while the proportion of trees ≤ 25 cm DBH increased and dominated in terms of density, basal area and biomass in all reforestations. Thus, the carbon sequestration potential clearly correlates to DBH size class, density and basal area of trees. Forests have a larger number of trees with large diameter and high values of basal area, hence resulting in larger amounts for carbon sequestration. On the other hand, it is usually observed small number of large trees and basal area values in the reforestation, which causes a low carbon sequestration. In the reforestation, there are more small DBH trees which this site is in an early stage of secondary succession.

Resulting from the reforesting effort is to restore a forest that still contains a fairly carbon sequestration with an apparently regenerating community structure. This should be considered as one of reforestation conservation success, even though the level of carbon sequestration was estimated slightly low compared to natural forests in Thailand. However, the reforestation of degraded forest lands has great potential to increase the rates of carbon sequestration from atmosphere in biomass and enhance biodiversity. The magnitude of this potential has not been widely quantified in Thailand, but it is important to develop national management policy and strategies.

In agricultural land, the potential of carbon sequestration of cultivated land depends on many factors such as type of crop and management practices. Although, fallow land accumulates less carbon than orchard trees, the fallow period allows some forest regrowth. Carbon sequestration in fallow land depends on original forest type and length of fallow, which vary across region. Crop cultivations usually have lower carbon sequestration than orchard and fallow land but carbon dynamic in crops varies within rotational time. There are two or three times of crop cultivation per year, these activities can increase and/or decrease carbon stocks in biomass. In addition, shorter rotation periods deplete carbon more rapidly.

CHAPTER IV

ESTIMATION OF BELOWGROUND CARBON AND SOIL ORGANIC CARBON

ABSTRACT

Soil organic carbon (SOC) and root carbon (RC) in 1 m depth were analyzed from natural forest, reforestation and agricultural land use in the Nam Yao sub-watershed, northern Thailand. In the forest, total soil organic carbon (TSOC) in hill evergreen forest was the highest as of 221.94 ± 1.66 Mg C ha^{-1}, followed by in the 14-year old reforestation as of 155.79 ± 3.35 Mg C ha^{-1}, and in 6-year fallow land as of 113.14 ± 2.26 Mg C ha^{-1}. The highest proportion of soil organic carbon was accumulated in 0-20 cm depth, more than 28.31% in the forest, more than 30.91% in the reforestation and more than 36.42% in agricultural land. For root carbon, it found that in hill evergreen forest was the highest as of 19.56 ± 0.11 Mg C ha^{-1}, followed by in the 26-year-old reforestation as of 11.14 ± 0.06 Mg C ha^{-1} and in agricultural land like orchard (*Litchi chinensis*) as of 1.04 ± 0.06 Mg C ha^{-1}. The proportion of root carbon was the highest in the 0-20 cm depth, more than 42.07% in the forest, more than 44.61% in the reforestation and more than 65.36% in the orchard land. The results also indicated that the conversion of forest land to agricultural land clearly reduces soil organic carbon and root carbon. SOC had significantly positive correlation with RC ($P < 0.05$). These relationships have remained relatively in all soil layers from 0 to 100 cm depth.

4.1 INTRODUCTION

Soil carbon pool, as the major part of the terrestrial carbon stock, plays an important role in the global carbon cycle. Therefore, the study of soil carbon dynamics is critically important to our ability to understand the carbon balance in the forests and their response to future global change (Davidson *et al*., 2000). Apparently, past deforestation and associated agricultural activities reduced soil organic carbon. Reforestation through plantation on abandoned and degraded agricultural lands in the tropics has been proposed as an effective carbon management approach (Montagnini and Porras, 1998). More carbon can be stored below ground by increasing the input rate of organic matter, increasing the depth of carbon stock, supporting the carbon density in the soils, and decreasing the carbon turnover rate in soils (Post and Kwon, 2000).

All the organic carbon found in the soil is primarily derived from plant. The two main processes of carbon in the soil are: (1) accumulation of soil organic matter due to the humification after plant death and (2) root exudates and other root-borne organic substances released into the rhizosphere during plant growth as well as sloughing of root hairs and fine roots by root elongation. The first mode of carbon sequestration is well documented, but carbon sequestration by plant roots is still under investigation. CO_2 fixed by crop plants and its translocation into the roots is a simultaneous process. Carbon is naturally added in the soil system by plant roots through root death, root exudates and root respiration. It is difficult to quantify the contribution of these three components separately (Kumar *et al*., 2006). Root biomass is typically estimated to be 20% of the aboveground forest carbon stocks (Ramankutty *et al*., 2007), but it is seldom measured due to the difficulties associated with sampling, particularly in forest areas.

Soils types in Thailand are diverse, developed over a wide range of parent materials and ecosystem, and comprise a larger C reservoir consisting of soil organic carbon. This chapter is aiming at (i) assessing the belowground carbon (BGC) in root and soil organic carbon (SOC) in three main land- use types: forest, reforestation and agricultural land and (ii) comparing the carbon sequestration potential between BGC and SOC. It is important to recognize that the belowground biomass associated with larger roots has not been included in the samples. Only roots size < 10 mm in diameter were retained and estimated both live and dead forms.

4.2 METHODS

4.2.1 Study site

The study was conducted in the Nam Haen watershed management unit (19°05'10"N, 100°37'02"E), Nam Yao sub-watershed, Nan Province from October 2005 to February 2006. The study was conducted in three main land-use types: forests, reforestations, and agricultural lands. The site collection was designed regarding Table 4.1.

Table 4.1 Study sites in Nam Haen watershed management unit area

Sites	Location	Type/vegetation	Plot size (m^2)	Plot Number
Forest				
HEF	47Q 0672295 UTM 2126899	Hill evergreen forest	50 x 50	8
DEF	47Q 0672344 UTM 2125649	Dry evergreen forest	50 x 50	8
MDF	47Q 0675457 UTM 2118240	Mixed deciduous forest	50 x 50	8
CSF	47Q 0680732 UTM 2115809	Mixed deciduous forest	50 x 50	4
CMF	47Q 0685006 UTM 2116906	Mixed deciduous forest	50 x 50	4
Reforestation				
RF26	47Q 0684082 UTM 2122527	*Gmelina aborea* Roxb.	50 x 50	4
RF19	47Q 0680748 UTM 2119676	*Eucalyptus camaldulensis* Dehn. *Tectona grandis* Linn.	50 x 50	4
RF14	47Q 0683003 UTM 2122381	*Tectona grandis* Linn.	50 x 50	4
RF10	47Q 0679903 UTM 2119368	*Tectona grandis* Linn. *Pterocarpus macrocarpus* Kurz. *Afzelia xylocarpa* (Kurz) Craib. *Acacia catechu* (L.f.) Willd, and *Pyrus malus* L.	50 x50	4
RF9	47Q 0680990 UTM 2119752	*Tectona grandis* Linn. *Pterocarpus macrocarpus* Kurz. *Afzelia xylocarpa* (Kurz) Craib. *Acacia catechu* (L.f.) Willd, and *Bauhinia vriegata* L.	50 x 50	4
Agriculture				
FL	47Q 0683820 UTM 2123305	Fallow land (5-6 years)	50 x 50	4
LT	47Q 0673679 UTM 2126388	*Litchi chinensis* Sonn. spp.	50 x50	4
Rice	47Q 0681248 UTM 2117440	*Oryza sativa* Linn.	1 x 1	10
Corn1	47Q 0673788 UTM 2126210	*Zea mays* Linn.	1 x 1	10
Corn2	47Q 0681215 UTM 2124023	*Zea mays* Linn.	1 x1	10

4.2.2 Soil sample

The plots were designed according to the methodology for aboveground inventory and biomass sampling. In each 50x50 m^2 plot, five sub plot of 10x10 m^2 were established at the corner and the center of plots, three soil cores were taken in each sub-plot from each layer, mixed samples as a composite sample from each layer. Samples were selected in 50x50 m^2 plot of forest, reforestation, fallow land and orchard tree and 1x1 m^2 plot of paddy field and corn field (n = 20 for each site). The soil samples were collected from surface down to 1 m depth, and separated into five layers of 0-20, 20-40, 40-60, 60-80 and 80-100 cm. In order to assess the SOC storage difference without damaging soil structure or altering SOC content, then soils were sampled adjacent to original former sampling sites from 50x50 cm^2 at 1 m deep pits. Moreover, soil was sampled at each horizon, and then bulk density was measured by using a cutting ring. This soil was collected and kept in plastic bags and sealed closely. Samples were oven-dried (105 °C for 48 hour) and bulk density was estimated as the mass of oven-dry soil divided by the core volume.

Soil samples for physical and chemical analyses were returned to the laboratory, air dried, and passed through a 2 mm sieve prior to analysis. Soil pH was mixed in a 1:1 soil to water suspension (weigh per volume) and measured with glass electrode by a pH meter (Thomas, 1996). Soil texture was analyzed by the hydrometer method after dispersion with sodium hexametaphosphate (Sheldrick and Wang, 1993). Determinations of bulk density were carried out by measurement of volume and weight, the result is in g cm^{-3} (Blake and Hartge, 1986). Total nitrogen (N) was measured by the classical Kjeldahl digestion method. Available phosphorus (P) was estimated by standard methods with the Bray II (Bray and Kurtz, 1945). Available potassium (K) was determined by extraction with 1 N ammonium acetate (NH_4OAc) at pH 7, and analyzed by atomic absorption spectrophotometer (Chapman,1965). Organic carbon contents in soil was determined from three replicates by using the Walkey-Black method (Walkley and Black, 1934). This method will oxidize only the organic carbon which carbonates do not interfere (Hesse, 1971). Soil organic carbon content from the original data was converted to soil organic matter by multiplying a constant of 1.724 (Soil Survey Laboratory Staff, 1996). Soil analysis was conducted at Soil Science Laboratory, Department of Agricultural Technology, King Mongkut

Institute of Technology Ladkrabang, Bangkok and Soil Science Laboratory, Department of Science and Agricultural Technology, Rajamangala University of Technology Lanna Nan based on Soil survey Staff (1975).

4.2.3 Root sample

The cores were sub-sampled for fine roots at 0-20, 20-40, 40-60, 60-80 and 80-100 cm depth intervals. Fine roots size ≤ 5 mm in diameter were separated by hand sorting and then successively sieved with a 2 and 1 mm mesh sieve to remove the remaining root fragments from soil in each layer. In order to determine an appropriate depth for sampling coarse roots, one, 1 x 1 m^2 pits were excavated to a depth of 100 cm. The pit was located in the center of 50 x 50 m^2 plot. Coarse roots (>5 mm) were removed in incremental depths of 0-20, 20-40, 40-60, 60-80 and 80-100 cm and transported to the laboratory. Coarse roots were separated from soil by hand. No species-wise classification of all roots was attempted. All roots were rinsed in tap water to remove mineral soil. After roots were washed and separated, they were dried to a constant weight at 70° C and weighed for 24h or to constant weight. Root materials were ground to a powder and carbon contents in root were analyzed using a CN Corder. The amounts of carbon of each sample were determined by multiplying dry weights of sample. The distribution of root carbon (RC) in each profile was calculated from the soil confined to a depth of 100 cm.

4.3 CALCULATION

The soil organic content of each layer was calculated as:

$$SOC = C \times BD \times H \qquad \text{(Equation 4.1)}$$

Where *SOC* are the density organic C (Mg C ha^{-1}) in each layer, *C* is organic carbon concentration (%), *BD* is the bulk density (g cm^{-3}), *H* is the thickness of each layer of the soil profile (20 cm).

Thus, the total soil organic carbon and fine root carbon of each soil profile was summed of soil organic carbon and fine root carbon in each layer down to 1 m depth.

4.4 STATISTICAL ANALYSIS

All information will be analyzed statistically by Software SPSS version 11.0. Differences in fine root carbon and soil organic carbon in each land-use type and between land-use types were analyzed using a One-way Analysis of Variance (ANOVA; within treatment and between treatments). Post-hoc multiple comparison method was used to compare a difference between and within treatments. Pearson correlation was used to test the relationship between soil properties and soil organic carbon and soil properties and fine root carbon.

4.5 RESULTS AND DISSCUSSION

4.5.1 Soil properties

Soil properties in all land-use types were shown in Appendix 4.1. Soil pH in all land use types was strongly acidic, with large variation among sites. In all sites, the soil pH was changed downwards and increased with depth in the soil profile. Soil in the rice field showed pH value significantly highest in all layers ($P < 0.05$). Soil pH at the 0-20 cm depth tended to be lowest in hill evergreen forest (4.03 ± 0.03) ($P < 0.05$).

The bulk density tended to increase when the soil depth increased. In comparison, soil bulk density tended to be greater in the agricultural sites compared to all forest and reforestation soils at all depth. Whilst the bulk density of fallow soil (AG1) was significantly lower than that in other agricultural soils ($P < 0.05$). The greatest overall bulk density in the agricultural land was about 2.10 g cm^{-3} at the 80-100 cm depth of rice field while the lowest bulk density was about 1.08-1.09 g cm^{-3} at the 0-20 cm depth of the 14-, 10-, and 9-year-old reforestation (Appendix 11).

As the results, the different land-use types indicated in relation to different soil texture (Appendix 11). In all land-use types, surface soil at 0-20 cm depth had noticeably higher sand content than the subsoil except mixed deciduous soil. It found that there are varied in soil textural classes of sites and layer. In all sites, clay content continued to increase slightly with depth except in the mixed deciduous, litchi and rice soils. Leaching of clay particles from surface soil to subsoil by rainfall is the one of possible reason making the surface soil rich in sand particle.

The organic matter in the forests and the reforestation soils had considerably higher than the organic matter in the agricultural soils except fallow soil in 0-40 cm depth. In the soil surface, the 14-year old reforestation soil (RF14) had organic matter significantly higher than other sites, while in the deeper soils in forest soils (20-40, 40-60 and 80-100 cm depth) was indicating significantly higher than in the reforestation and agricultural soils ($P< 0.05$). However, at the 60-80 cm depth, soil organic matter in forest soil and reforestation soil were similar.

The results showed that soil properties changes associated with land-use changes from the forest to the agricultural land. In the forest and the reforestation, the surface soils (0-40 cm) were highly acidic, affected by the cover litter all year. In agricultural land, the different pH from other land-use type is possibly attributed to liming and burning practices. Moreover, the long term of compost and chemical fertilizers uses possibly effected to soil pH and soil properties (Park *et al*., 2004). Generally, changes in soil pH may also alter the ability of soils to retain carbon and nutrients (Krishnaswamy and Richter, 2002). As the results, the study showed that the bulk density was found higher in the agricultural soil than in the forest and reforestation soils, since agricultural practices could lead to soil compaction (Post and Kwon, 2000). The fallow site can lead to a rapid decreasing in soil bulk density compared to other agricultural lands. This indicated that the reforestation of agricultural land restoring to natural forest land was in transition period of changing from previous human disturbed condition to recovery natural soil condition or even close.

4.5.2 Soil carbon and nitrogen

In all soil layers, total soil nitrogen (N) was found the highest in the mixed deciduous forest. It was similar to the 14-year old reforestation (0-20 cm depth), dry evergreen forest (20-60 and 80-100 cm depth) and 9- and 10-year old reforestation (60-80 cm depth) ($P < 0.05$). In 0-40 cm depth, total N in the forest and reforestation soils were significantly higher than the agricultural soils except fallow soil, while total N in the forest and reforestation soils was lower than all agricultural soils at 40-100 cm depth ($P < 0.05$). The soil N tended to disappear at 80-100 cm depth (< 7% of total N). Soil N Changes in land use also effected carbon-nitrogen (C:N) ratios (Appendix 12). The C:N ratios tended to decrease in the subsoil. However, ratios narrowly varied less than 1 through the soil profile. In all layers, C:N ratios tended to be lower in the rice paddy field and corn fields compared to other land-use types, although they were not significant at the 80-100 cm depth ($P < 0.05$).

Importantly, the result shows that C:N ratio in all land-use types was relatively low. According to the findings, the C:N ratio in agricultural land was lower than that of the forest and the reforestation. This means that carbon mineralization per unit of mineralized N was considerably higher in the forest and the reforestation than agricultural land, which could indicate that decomposition rates are more sensitive in forest soil than in agricultural soil (Grunzwig *et al.*, 2004). However, organic carbon in a soil in a function of the N content of the soil and as such SOC can not be increased without increasing soil N content (Martens *et al.*, 2003).

4.5.3 Soil organic carbon (SOC)

The total of SOC in each site at 1 m depth in soil showed in table 4.2. The amounts SOC content tended to be greater in the forest sites compared to all reforestation and agricultural sites in all depths ($P< 0.05$). The concentration of total SOC at 1 m depth was significantly highest in the hill evergreen forest (221.94 ± 1.66 Mg C ha^{-1}), while SOC content at 1 m depth in the first sites of corn field was the lowest (113.14 ± 2.26 Mg C ha^{-1}). In all depths of soil samples, the concentration of SOC in all forest sites was significantly greater than agricultural sites except fallow site at 0-20 cm depth ($P< 0.05$). The hill evergreen and dry evergreen forest had the highest amount of SOC of all soil types at that depth. In the reforestation, the concentration of SOC at 1 m depth was higher than that in all agricultural sites ($P< 0.05$). Total SOC in the 14- and 26-year-old reforestation (155.79 ± 3.35 Mg C ha^{-1} and 151.61 ± 3.66 Mg C ha^{-1}) were significantly greater than other reforestation sites. Although SOC content in the 26-year-old reforestation was similar to the fallow and litchi sites at 0-40 cm depth, while in deeper soil (40-100 cm depth), SOC concentration in all reforestation sites tended to be higher than that in all agricultural sites ($P< 0.05$). In the agricultural land, the concentration of total SOC at 1 m depth was significantly highest in the fallow land (113.14 ± 2.26 Mg C ha^{-1}), especially at 0-40 cm depth, SOC content was significantly higher than that in other agricultural sites.

There was a consistent pattern for amounts of SOC at all layer down to 100 cm depth, increasing in the forest more than the reforestation and the agricultural land. Comparing amounts of SOC between land-use types, the forest had the highest and the agricultural land had the lowest amount of SOC at all depth. At the 0-20 cm depth, the forest had a higher amount of SOC than all other land-uses types (Table 4.2, Fig. 4.1). All land-use types, soils contained higher amounts of SOC in the upper 20 cm layer than in the other layers. The SOC content ranged from 28 to 30%, 30 to 38% and 36 to 48% in the forest, the reforestation and the agricultural soils, respectively, of total SOC at 1 m depth. At the 20-40 cm depth, all soils contained more than 20%, and a considerably small proportion at the 80-100 cm depth, soils contained lower than 10% of total SOC at 1 m depth.

As the results, the SOC at 1 m depth in the forest corresponded to the range of other forests in Thailand (Appendix 13). The studies of SOC in *Tectona grandis* Linn reforestation indicated that SOC at 1 m depth in the reforestation of. this study of 14-year old was 155.79 Mg C ha^{-1} which was higher than the 22-year-old reforestation in Lampang (137.20 Mg C ha^{-1}) (Hiratsuka *et al*., 2005) but lower than the 11-12-year-old in Kanchanaburi (195.20 Mg C ha^{-1}); the 17-18-year-old (151.00 Mg C ha^{-1}) (Janmahasatien and Phopinit, 2001); and the 17-year-old in Lampang (211.40 Mg C ha^{-1}) (Hiratsuka *et al*., 2005). In case of the other countries, the SOC at 1 m depth of the forest in this study was 163.91 - 221.94 Mg C ha^{-1}, which was in the range of the pine-oak and fragmented forest in Mexico (166.00-215.00 Mg C ha^{-1}) (Mendoza-Vega *et al*., 2003). Overall, the SOC at 1 m depth of the agricultural land in this study was 77.57 – 113.14 Mg C ha^{-1}, which was lower than the grassland and cropland in Mexico (135.00 Mg C ha^{-1}) due to a greater aboveground carbon in Mexico (29.00 Mg ha^{-1} in fragmented forest, 127.50 Mg ha^{-1} in pine-oak forest, 12.00 Mg ha^{-1} in grassland and cropland, Mendoza-Vega *et al*., 2003).

The gain or loss of soil C from reforestation is likely to depend strongly on the intensity of past land use practices (Silver *et al*., 2000). The soil C sequestration of the agricultural land was a big change which is likely to be the consequence of the reduced amount of organic material being returned to the soil system, and high rates of oxidation of soil organic matter due to tillage (Sperow *et al.*, 2003). These results suggest that there are many factors and processes that determine the direction and rate of change in SOC content when vegetation and soil management practices are changed (Post and Kwon, 2000). The forest also has a higher amount of SOC compared to other land-use types, which this is probably due to the larger amount of aboveground carbon, resulting in greater litter input (Mendoza-Vega *et al*., 2003).

The reforestation resulted in a large increase in SOC stocks but it was lower than that of the forest. However, the results showed that SOC accumulated faster in the upper 20 cm layer of reforestation than in the forest. Silver *et al.* (2004) found that the significant SOC sequestration can occur with reforestation of land use over time. It supports that the maintenance of older reforested sites can yield significant SOC particularly C sequestration which is likely to occur in older reforested and afforested ecosystem. In the agricultural land, SOC is likely to increase when cultivated soil is planted with permanent vegetation. The losses of SOC from cropped land use have been linked to soil disturbance and change in plant litter especially by conversion of native vegetation to cultivated crops, which caused a rapid decline in soil organic matter (Murty *et al*., 2002). The SOC decrease continues depending on the land use practice on the land. If the land is abandoned and the forest re-grows, the SOC stocks can be accumulated again. It clearly indicated a full recovery of SOC stocks result from deforestation and intensity of land use (Ramankutty *et al*., 2006).

In relationship of SOC and soil depth, the results clearly showed the differences of SOC vertical distribution (Figure 4.1). The highest SOC was found at the surface soil (Mendoza-Vega *et al*., 2003, Chowdhury *et al*., 2007). Plant functional types significantly affected the vertical distribution of SOC. In this study, the percentage of SOC in 0-20 cm in the forest and the reforestation (29% and 35%, respectively) were lower than proportion of SOC in the world forests. Jobbágy and Jackson (2000) showed that the percentage of SOC in the top 20 cm soil depth (relative to the first meter) averaged 33%, 42%, and 50% for shrublands, grasslands, and forests, respectively. Differences could also be expected from climatic condition between other regions of the world. The cropland (rice and corn) soils in this study also have a similar proportion of SOC in 0-20 cm (45%) in corresponding to the world average of 41% studied by Jobbágy and Jackson (2000). It suggests that SOC in agricultural soils have been sequestered towards moderates in the rest of the world.

In comparison with the study of Mendoza-Vega *et al*. (2000), this study found proportionally less SOC at the surface (0-20 cm) than that was found in other pine-oak and fragmented forests, cultivated land and grassland. All land-use types, soils contained higher amounts of SOC in the upper 40 cm layer (> 53% in the forest and the reforestation; and > 61% in agricultural soils). This study also indicated that more than 50% of total SOC in soil deposited in the 0-40 cm depth.

Table 4.2 Soil organic carbon in different land-use types (Mg C ha^{-1})

Land use type	0-20 cm	% of total	20-40 cm	% of total	40-60 cm	% of total	60-80 cm	% of total	80-100 cm	% of total	0-100 cm	% of total
HEF	68.05 ± 0.54 a	30.66	56.16 ± 0.65 a	25.30	47.32 ± 0.81 a	21.32	28.02 ± 0.76 a	12.63	22.39 ± 0.79 a	10.09	221.94 ± 1.66 a	100.00
DEF	65.36 ± 1.15 b	30.50	54.45 ± 0.67 b	25.41	46.74 ± 0.56 a	21.81	26.18 ± 0.51 b	12.22	21.54 ± 0.82 a	10.06	214.29 ± 1.97 b	100.00
MDF	54.36 ± 0.64 d	29.91	48.24 ± 0.71 c	26.54	40.26 ± 0.94 c	22.15	21.40 ± 1.34 e	11.78	17.49 ± 0.79 b	9.62	181.76 ± 2.46 c	100.00
CSF	46.44 ± 0.77 f	28.33	41.78 ± 1.02 e	25.66	37.77 ± 0.91 d	23.04	22.79 ± 0.68 d	14.00	14.02 ± 0.82 c	8.61	163.91 ± 4.90 e	100.00
CMF	48.70 ± 0.77 e	28.31	44.16 ± 1.19 d	25.67	41.45 ± 0.77 b	24.10	22.99 ± 0.99 d	13.37	14.70 ± 0.54 c	8.55	171.54 ± 2.97 d	100.00
RF26	57.81 ± 3.47 c	38.13	34.70 ± 1.04 fg	22.89	26.26 ± 1.05 f	17.32	23.24 ± 1.77 cde	15.33	9.60 ± 0.81 e	6.33	151.61 ± 3.66 f	100.00
RF19	45.43 ± 1.36 fg	32.51	32.18 ± 1.27 h	23.03	28.97 ± 0.91 e	20.73	22.75 ± 1.36 de	16.28	10.40 ± 1.18 de	7.44	139.73 ± 1.80 h	100.00
RF14	68.87 ± 1.11 a	44.21	31.88 ± 1.42 h	20.46	25.87 ± 2.70 f	16.61	17.47 ± 1.40 f	11.22	11.69 ± 1.34 d	7.50	155.79 ± 3.35 f	100.00
RF10	47.01 ± 1.98 efg	32.10	34.78 ± 1.83 fg	23.75	28.33 ± 1.22 e	19.35	25.08 ± 1.72 bc	17.13	11.24 ± 1. d	7.68	146.44 ± 4.51 g	100.00
RF9	43.45 ± 1.30 h	30.91	35.65 ± 1.34 f	25.37	28.31 ± 3.04 ef	20.14	23.57 ± 0.68 cd	16.77	9.57 ± 0.73 e	6.81	140.57 ± 4.54 h	100.00
FL	55.20 ± 2.33 cd	48.78	34.00 ± 1.31 g	30.05	11.26 ± 1.50 j	9.95	7.26 ± 1.21 h	6.41	5.43 ± 0.78 g	4.80	113.14 ± 2.26 i	100.00
Litchi	36.71 ± 1.11 ij	36.42	31.27 ± 0.62 h	31.03	16.86 ± 0.90 g	16.73	10.57 ± 0.47 g	10.49	5.37 ± 0.89 g	5.33	100.79 ± 1.97 k	100.00
Rice	45.03 ± 1.18 g	43.06	26.79 ± 0.60 i	25.62	15.76 ± 0.61 h	15.07	10.23 ± 0.74 g	9.78	6.77 ± 0.51 f	6.47	104.58 ± 0.99 j	100.00
Corn1	35.59 ± 1.32 j	45.88	16.12 ± 1.24 k	20.78	13.95 ± 0.78 i	17.99	7.77 ± 0.42 h	10.02	4.13 ± 0.24 h	5.32	77.57 ± 1.38 m	100.00
Corn2	37.36 ± 0.81 i	45.62	20.24 ± 0.44 j	24.71	14.24 ± 0.81 i	17.99	5.87 ± 0.69 i	7.17	4.19 ± 0.17 h	5.12	81.90 ± 1.56 l	100.00

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

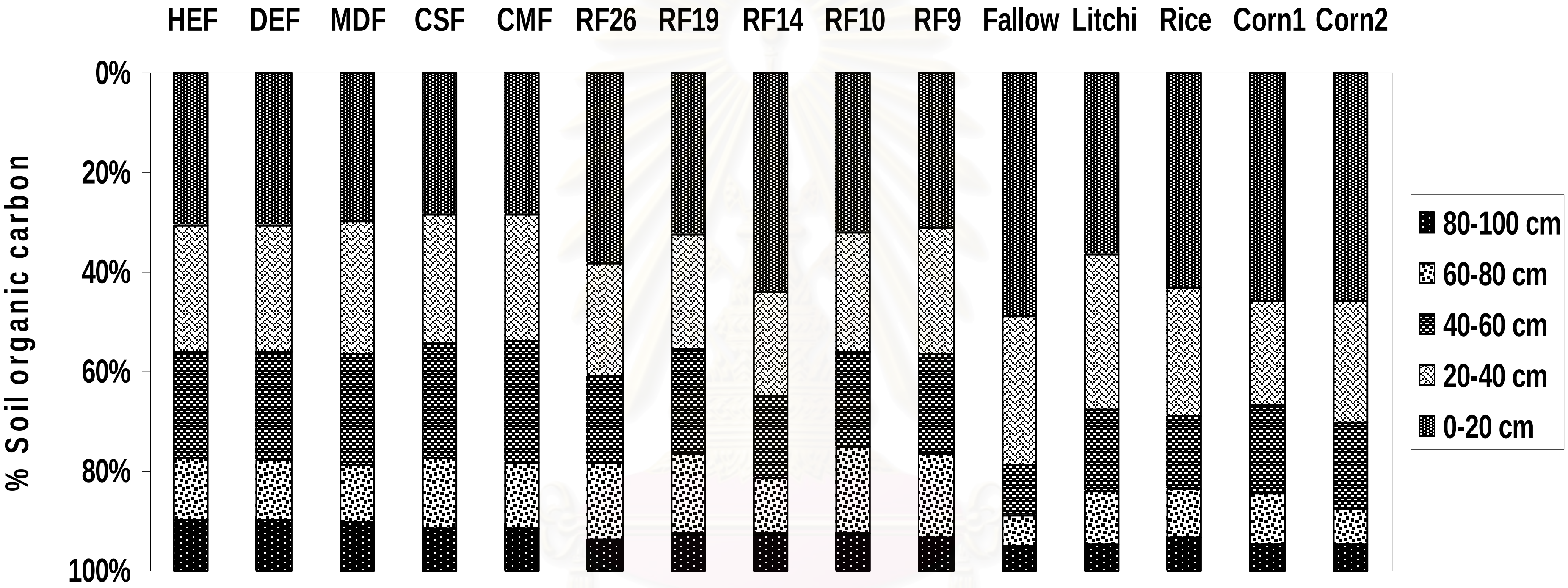


Figure 4.1 Distribution of soil organic carbon in different land-use types

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

4.5.4 Root carbon (RC)

Mean amounts of fine root carbon (FRC; ≤ 5 mm in diameter) from each land-use types were shown in Table 4.3. In all depths, FRC content was greater in all forest and reforestation sites compared to that in all agricultural sites ($P < 0.05$). The amount of FRC was the highest in hill evergreen forest and decreased to the lowest value in the corn fields. In all land-use types, there was a decrease in the amount of FRC related to a increase in depth. Results showed that the largest amount of FRC down to 1 m depth was considerably contained in the upper 20 cm layer and the least amount of FRC was also contained in the 80-100 cm layer (< 3.31%). The distribution of FRC content was the highest at 0-20 cm depth, the forest and the reforestation held more than 41% while the agricultural land held more than 68% of total FRC in 1 m soil depth (Table 4.3 and Fig. 4.2). FRC was completely absent in rice paddy field and corn fields at 60-80 cm and 80-100 cm depth.

The total FRC in 1 m soil depth is shown in Table 4.3, which was the highest in hill evergreen forest (4.74 ± 0.10 Mg C ha^{-1}) while the 6-year-old fallow land had the lowest FRC (0.47 ± 0.04 Mg C ha^{-1}) in 1 m soil depth. Over all, FRC in the forest and the reforestation were about 4 to 10 times and 3 to 8 times greater respectively than FRC in agricultural land.

The amounts of FRC showed some differences between the land-use types that were consistent with differences in SOC. The large variation in amounts of FRC was the large variation in the content of the roots (Mendoza-Vega *et al*., 2003). In all land-use types, the highest FRC was found in the surface layer (0-20 cm depth). In a similar analysis, Mendoza-Vega *et al*. (2003) also observed highest FRC in different land-use types that contained in the upper 20 cm. Overall, fine roots have been observed that was concentrated at horizon interfaces and decreased in abundance with depth. Steele *et al*. (1997) also indicated that fine roots are found most abundant in the uppermost soil layer and decrease in frequency continuously with depth. Nonetheless, the fine root location in the upper part of the soil profile seems to be influenced by the availability of nutrients in the soil (Schmid and Kazda, 2002). In addition, inter-specific competition, forest floor and soil moisture content are known to influence fine root distributions (Hodge *et al*., 1999). In deeper layer, soils contained higher amounts of FRC in the upper 40 cm layer than in the 40-100 cm layer. This could relate to the fact that the upper soil contains fine roots of tree and vegetation that plays an important role in the C and nutrient dynamics of soils.

The FRC proportion found in this study can be applied to evaluate the situation of FRC in soil in difference land-use type in Thailand. The proportion of FRC at 0-20 cm depth also contained 42-49% in the forest and the reforestation and 66-80% in agricultural land, which were nearly similar to FRC proportion in Mexico at about >50% in pine-oak forest, and > 80% in grassland and cropland (Mendoza-Vega *et al*., 2003).

Although several studies suggest that the conversion of forests to open land (grassland and cropped land) potentially reduces soil organic carbon (SOC) and fine root carbon (FRC). Agricultural lands are believed to be a major potential sink and could absorb large quantities of C if trees are reintroduced to these systems and discreetly managed together with crops and/or animal (Albrecht and Kandji, 2003). As the loss of C from cropped land has been linked to soil disturbance, Lal (2002) suggested that appropriate agricultural practices including the conversion of upland to rice paddies, integrated nutrient management, crop rotations that return large quantities of biomass, and conservation-effect systems could help to enhance the SOC stock.

Mean amounts and distribution of coarse root carbon (CRC; > 5 mm in diameter) in the soil profile for each land-use types had a similar trend with amounts and distribution of FRC (≤ 5 mm) (Table 4.4). In 0-40 cm depth, amount of CRC (> 5 mm) in all forest and the reforestation sites were greater than that in the fallow and Litchi sites, although not significant between the forest and the reforestation sites. However amount of CRC in all forest sites was greater than that in all reforestation and agricultural sites ($P < 0.05$). In agricultural land, the CRC content disappear in the rice and corn fields. The largest amounts of CRC down to 1 m were contained in the upper 20 cm and the least amount of CRC contained in 80-100 cm depth (< 4%). In 0-20 cm depth, the forest, the reforestation and the agricultural land held 41-45%, 44-48% and 68-69%, respectively, of total CRC at 1 m depth. Total CRC in 1 m depth was the highest in hill evergreen forest (14.82 ± 0.10 Mg C ha^{-1}) while the Litchi sites had the smallest FRC (0.49 ± 0.05 Mg C ha^{-1}) in 1 m soil depth. Overall, CRC in the forest and the reforestation were about 21 to 30 times and 12 to 15 times greater respectively than FRC in agricultural land.

The total root carbon (TRC; sum of FRC ≤ 5 mm and CRC > 5 mm in diameter) was shown in Table 4.5. Due to the larger root diameter in the forest compared to that in the other land-use types, total RC in 1 m depth increased when FRC and CRC were expanded. The distribution of TRC content was the greatest in 0-20 cm depth, the forest and the reforestation held more than 42% while the agricultural land held more than 65% of TRC in 1 m depth (Table 4.5, Fig. 4.4).The main fraction of TRC in 1 m depth was composed by CRC. CRC (> 5 mm) was about three times, two times and one time greater than FRC (≤ 5 mm diameter) for the forest, the reforestation and agricultural land.

The differences between the forest and the other land-use types in amounts of SOC and FRC are clear at the 40-100 cm depth interval. A higher amount of FRC at deeper levels for forests results in higher root litter input, which can explain in the differences in the amount of SOC in deeper layers.

Table 4.3 Fine root carbon (≤ 5 mm) in different land-use types (Mg C ha^{-1})

Land use type	0-20 cm	% of total	20-40 cm	% of total	40-60 cm	% of total	60-80 cm	% of total	80-100 cm	% of total	0-100 cm	% of total
HEF	2.10 ± 0.03 a	44.30	1.25 ± 0.03 a	21.16	0.85 ± 0.03 a	17.93	0.44 ± 0.02 a	9.28	0.10 ± 0.01 a	2.11	4.74 ± 0.10 a	100.00
DEF	1.80 ± 0.03 b	43.37	1.09 ± 0.01 b	26.27	0.74 ± 0.02 b	17.83	0.43 ± 0.02 a	10.36	0.09 ± 0.01 b	2.17	4.15 ± 0.06 b	100.00
MDF	1.62 ± 0.02 de	42.74	1.06 ± 0.01 c	27.97	0.70 ± 0.01 c	18.47	0.34 ± 0.01 b	8.97	0.07 ± 0.01 c	1.85	3.80 ± 0.04 c	100.00
CSF	1.60 ± 0.02 e	43.48	1.01 ± 0.01 e	27.45	0.68 ± 0.02 de	18.48	0.33 ± 0.01 b	8.97	0.06 ± 0.01 e	1.63	3.68 ± 0.04 e	100.00
CMF	1.63 ± 0.01 cd	43.47	1.01 ± 0.02 e	26.93	0.70 ± 0.02 cd	18.67	0.34 ± 0.02 b	9.07	0.07 ± 0.01 cd	1.87	3.75 ± 0.04 d	100.00
RF26	1.61 ± 0.01 e	44.40	1.01 ± 0.01 e	27.90	0.64 ± 0.01 f	17.68	0.30 ± 0.01 c	8.29	0.06 ± 0.01 d	1.66	3.62 ± 0.03 f	100.00
RF19	1.61 ± 0.01 e	50.00	0.87 ± 0.01 g	31.56	0.50 ± 0.01 g	15.53	0.20 ± 0.01 e	6.21	0.04 ± 0.00 f	1.24	3.22 ± 0.02 h	100.00
RF14	1.79 ± 0.02 b	50.00	1.13 ± 0.01 d	25.21	0.41 ± 0.01 h	11.45	0.18 ± 0.01 f	5.03	0.07 ± 0.01 cd	1.96	3.58 ± 0.03 g	100.00
RF10	1.79 ± 0.01 b	49.04	0.92 ± 0.01 f	28.03	0.67 ± 0.01 e	18.36	0.22 ± 0.01 d	6.03	0.05 ± 0.01 e	1.37	3.65 ± 0.02 ef	100.00
RF9	1.33 ± 0.01 f	50.38	0.74 ± 0.01 h	25.00	0.40 ± 0.01 i	15.15	0.13 ± 0.01 g	4.92	0.04 ± 0.01 f	1.52	2.64 ± 0.02 i	100.00
FL	0.68 ± 0.01 h	70.83	0.25 ± 0.01 i	25.00	0.03 ± 0.01 j	3.13	0.01 ± 0.00 h	1.04	0.00 ± 0.00 g	0.00	0.96 ± 0.02 k	100.00
Litchi	0.51 ± 0.01 i	68.00	0.21 ± 0.01 i	28.00	0.02 ± 0.01 j	2.67	0.01 ± 0.00 h	1.33	0.00 ± 0.00 g	0.00	0.75 ± 0.01 l	100.00
Rice	0.38 ± 0.05 j	80.85	0.08 ± 0.02 k	17.02	0.01 ± 0.01 k	2.13	0.00 ± 0.00 i	0.00	0.00 ± 0.00 g	0.00	0.47 ± 0.06 m	100.00
Corn1	0.82 ± 0.07 g	85.42	0.13 ± 0.04 j	13.54	0.01 ± 0.02 j	1.04	0.00 ± 0.00 i	0.00	0.00 ± 0.00 g	0.00	0.96 ± 0.05 j	100.00
Corn2	0.84 ± 0.07 g	84.00	0.14 ± 0.04 j	14.00	0.02 ± 0.01 jk	2.00	0.00 ± 0.00 i	0.00	0.00 ± 0.00 g	0.00	1.00 ± 0.06 j	100.00

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

Table 4.4 Coarse root carbon (>5 mm) in different land-use types (Mg C ha^{-1})

Land use type	0-20 cm	% of total	20-40 cm	% of total	40-60 cm	% of total	60-80 cm	% of total	80-100 cm	% of total	0-100 cm	% of total
HEF	6.13 ± 0.03 a	41.36	3.65 ± 0.01 a	24.63	2.67 ± 0.01 a	18.02	1.83 ± 0.01 a	12.35	0.54 ± 0.01 a	3.64	14.82 ± 0.10 a	100.00
DEF	5.57 ± 0.03 b	45.77	3.42 ± 0.02 b	28.10	1.89 ± 0.01 e	15.53	0.96 ± 0.01 d	7.89	0.32 ± 0.01 b	2.63	12.16 ± 0.06 b	100.00
MDF	5.07 ± 0.04 c	42.36	3.35 ± 0.03 c	27.99	2.26 ± 0.01 b	18.88	1.00 ± 0.01 c	8.35	0.29 ± 0.01 c	2.42	11.97 ± 0.04 c	100.00
CSF	4.45 ± 0.05 e	42.95	2.86 ± 0.02 d	27.61	1.92 ± 0.01 d	18.53	0.93 ± 0.01 e	8.98	0.20 ± 0.01 d	1.93	10.36 ± 0.04 e	100.00
CMF	4.74 ± 0.05 d	43.21	2.78 ± 0.01 e	25.34	2.00 ± 0.01 c	18.23	1.17 ± 0.01 b	10.67	0.28 ± 0.01 c	2.55	10.98 ± 0.04 d	100.00
RF26	3.37 ± 0.07 f	44.81	2.11 ± 0.05 f	28.06	1.31 ± 0.03 f	17.42	0.58 ± 0.03 f	7.71	0.15 ± 0.01 e	2.00	7.52 ± 0.15 f	100.00
RF19	2.97 ± 0.11 h	48.21	1.62 ± 0.06 h	26.30	1.04 ± 0.05 h	16.88	0.42 ± 0.02 g	6.82	0.11 ± 0.01 g	1.79	6.16 ± 0.24 h	100.00
RF14	3.43 ± 0.12 f	47.44	2.04 ± 0.06 g	28.22	1.20 ± 0.06 g	16.60	0.45 ± 0.03 g	6.22	0.11 ± 0.01 g	1.52	7.23 ± 0.25 g	100.00
RF10	3.17 ± 0.09 g	44.40	2.01 ± 0.08 g	28.15	1.28 ± 0.05 f	17.93	0.54 ± 0.04 f	7.56	0.14 ± 0.01 f	1.96	7.13 ± 0.21 g	100.00
RF9	2.92 ± 0.09 h	48.03	1.61 ± 0.05 h	26.48	1.03 ± 0.06 h	16.94	0.42 ± 0.03 g	6.91	0.10 ± 0.01 g	1.64	6.08 ± 0.22 h	100.00
FL	0.37 ± 0.06 i	68.52	0.12 ± 0.01 i	22.22	0.04 ± 0.01 i	7.41	0.01 ± 0.00 h	1.85	0.00 ± 0.01 h	0.00	0.54 ± 0.06 i	100.00
Litchi	0.34 ± 0.04 i	69.40	0.11 ± 0.01 i	22.46	0.03 ± 0.01 i	6.13	0.01 ± 0.00 h	2.01	0.00 ± 0.01 h	0.00	0.49 ± 0.05 i	100.00
Rice	0.00 ± 0.00 j	0.00	0.00 ± 0.00 j	0.00	0.00 ± 0.00 j	0.00	0.00 ± 0.00 i	0.00	0.00 ± 0.00 h	0.00	0.00 ± 0.00 j	100.00
Corn1	0.00 ± 0.00 j	0.00	0.00 ± 0.00 j	0.00	0.00 ± 0.00 j	0.00	0.00 ± 0.00 i	0.00	0.00 ± 0.00 h	0.00	0.00 ± 0.00 j	100.00
Corn2	0.00 ± 0.00 j	0.00	0.00 ± 0.00 j	0.00	0.00 ± 0.00 j	0.00	0.00 ± 0.00 i	0.00	0.00 ± 0.00 h	0.00	0.00 ± 0.00 j	100.00

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

Table 4.5 Total root carbon in different land-use types (Mg C ha^{-1})

Land use type	0-20 cm	% of total	20-40 cm	% of total	40-60 cm	% of total	60-80 cm	% of total	80-100 cm	% of total	0-100 cm	% of total
HEF	8.23 ± 0.04 a	42.07	4.90 ± 0.03 a	25.05	3.52 ± 0.02 a	18.00	2.27 ± 0.03 a	11.61	0.64 ± 0.01 a	3.27	19.56 ± 0.11 a	100.00
DEF	7.37 ± 0.05 b	45.19	4.51 ± 0.03 b	27.65	2.63 ± 0.02 d	16.13	1.39 ± 0.02 c	8.52	0.41 ± 0.01 b	2.51	16.31 ± 0.11 b	100.00
MDF	6.70 ± 0.04 c	42.49	4.41 ± 0.03 c	27.96	2.96 ± 0.02 b	18.77	1.34 ± 0.02 d	8.50	0.36 ± 0.01 c	2.28	15.77 ± 0.11 c	100.00
CSF	6.05 ± 0.06 e	43.09	3.87 ± 0.03 d	27.56	2.60 ± 0.02 d	18.52	1.26 ± 0.01 e	8.98	0.26 ± 0.01 d	1.85	14.04 ± 0.10 e	100.00
CMF	6.37 ± 0.05 d	43.24	3.80 ± 0.02 e	25.80	2.70 ± 0.02 c	18.33	1.51 ± 0.02 b	10.25	0.35 ± 0.01 c	2.38	14.73 ± 0.06 d	100.00
RF26	4.97 ± 0.07 g	44.61	3.13 ± 0.05 f	28.10	1.95 ± 0.03 e	17.51	0.88 ± 0.04 f	7.90	0.21 ± 0.01 e	1.88	11.14 ± 0.18 f	100.00
RF19	4.58 ± 0.11 h	48.83	2.49 ± 0.06 h	26.54	1.54 ± 0.05 g	16.42	0.63 ± 0.02 h	6.72	0.14 ± 0.02 g	1.49	9.38 ± 0.24 h	100.00
RF14	5.22 ± 0.12 f	48.25	3.17 ± 0.07 f	29.30	1.62 ± 0.06 f	14.97	0.63 ± 0.03 h	5.82	0.18 ± 0.02 f	1.66	10.82 ± 0.26 g	100.00
RF10	4.96 ± 0.09 g	45.97	2.93 ± 0.08 g	27.16	1.95 ± 0.05 e	18.07	0.76 ± 0.04 g	7.04	0.19 ± 0.01 f	1.76	10.79 ± 0.21 g	100.00
RF9	4.25 ± 0.09 i	48.68	2.35 ± 0.05 i	26.92	1.43 ± 0.06 h	16.38	0.56 ± 0.03 i	6.42	0.14 ± 0.01 g	1.60	8.73 ± 0.22 i	100.00
FL	0.66 ± 0.07 l	65.36	0.25 ± 0.02 j	24.75	0.08 ± 0.01 i	7.92	0.02 ± 0.00 j	1.98	0.00 ± 0.00 h	0.00	1.01 ± 0.07 j	100.00
Litchi	0.69 ± 0.04 l	66.35	0.25 ± 0.02 j	24.04	0.08 ± 0.01 i	7.69	0.02 ± 0.00 j	1.92	0.00 ± 0.00 h	0.00	1.04 ± 0.06 j	100.00
Rice	0.38 ± 0.05 m	80.85	0.08 ± 0.02 l	17.02	0.01 ± 0.01 j	2.13	0.00 ± 0.00 k	0.00	0.00 ± 0.00 h	0.00	0.47 ± 0.06 k	100.00
Corn1	0.77 ± 0.04 k	80.21	0.17 ± 0.02 k	17.71	0.02 ± 0.02 j	2.08	0.00 ± 0.00 k	0.00	0.00 ± 0.00 h	0.00	0.96 ± 0.05 j	100.00
Corn2	0.82 ± 0.04 j	82.00	0.16 ± 0.02 k	16.00	0.02 ± 0.01 j	2.00	0.00 ± 0.00 k	0.00	0.00 ± 0.00 h	0.00	1.00 ± 0.06 j	100.00

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

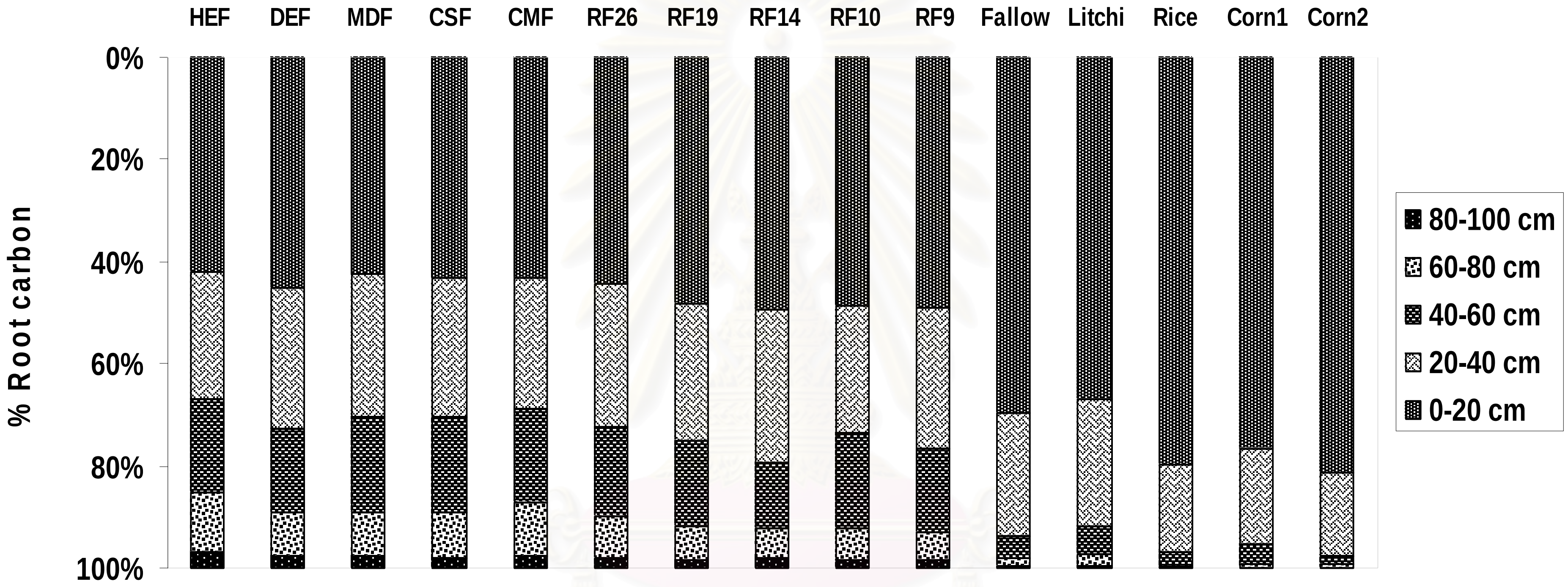


Figure 4.2 Distribution of root carbon in different land-use type

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old) and RF9 = Reforestation which planted in 1996 (9-year-old)

4.5.5 Changes in soil properties and its relationship to soil organic carbon (SOC) and root carbon (RC)

As shown in Table 4.6 and 4.7, the amount of SOC in each layer was significantly correlated with soil bulk density, soil pH, and soil nutrients. SOC and RC concentration had significantly negative correlation with both soil bulk density and soil pH ($P < 0.05$). Increases in soil bulk density also affected to SOC and RC in reducing litter input and ultimately causing a loss of SOC and RC. The strong correlation between bulk density of SOC and RC, show that SOC and RC stocks were reduced while soil bulk density increased in all land-use types. Zhang *et al.* (2004) suggested that the increase in bulk density could be a primary factor responsible for observed soil C decline. SOC concentration and bulk density are negatively correlated with each other in many soils. This correlation has been used widely to estimate bulk densities from SOC concentrations (Crowe *et al.*, 2006).Our results indicate that the SOC and RC stock potential on individual sites was weak correlated with soil pH, even it was not significant at 60-80 cm depth. This result is similar to that of Bronson *et al.* (1998) who reported that the SOC of upland soils of Sumatra, Indonesia decreased by 15% for every unit increase in soil pH. In contrast to that, SOC and RC content had significantly positive correlation with soil N and K ($P < 0.05$). While SOC and RC content were weak correlated with soil P, they might be significant in some depth. These results indicate that the relationships between SOC and soil properties & soil nutrients as well as between RC and soil properties & soil nutrients were similar regarding SOC had significantly positive correlation with RC ($P < 0.05$). And these relationships have remained relatively in all soil layers.

Table 4.6 Correlation between SOC and soil properties

Variable	Bulk density	Soil pH	Soil N	Soil P	Soil K
0-20 cm	-0.599**	-0.391**	0.850**	0.269**	0.655**
20-40 cm	-0.559**	-0.394**	0.919**	0.030	0.641**
40-60 cm	-0.331**	-0.292**	0.951**	0.333**	0.703**
60-80 cm	-0.588**	-0.042	0.900**	0.231**	0.347**
80-100 cm	-0.304**	-0.292**	0.908**	0.397**	0.744**

** correlation is significant at the 0.05 level

Table 4.7 Correlation between RC and soil properties

Variable	Bulk density	Soil pH	Soil N	Soil P	Soil K	SOC
0-20 cm	-0.663**	-0.622**	0.618**	0.066	0.715**	0.645**
20-40 cm	-0.560**	-0.491**	0.817**	0.027	0.660**	0.878**
40-60 cm	-0.410**	-0.309**	0.912**	0.312**	0.687**	0.942**
60-80 cm	-0.271**	-0.095	0.578**	0.338**	0.678**	0.783**
80-100 cm	-0.361**	-0.134*	0.790**	0.345**	0.747**	0.930**

*   correlation is significant at the 0.01 level

** correlation is significant at the 0.05 level

4.6 CONCLUSION

The results reveal that significant C sequestration in soils can occur in the forest and also highlight the value of reforestation for a great potential to increase C sequestration. It is clear that deforestation and changes in land use have produced severe major losses in soil C stocks in form of soil organic matter content. An accumulation of roots in different land-use types has a large variation in amounts of root C. Therefore, changes in soil properties and soil nutrients apparently affected to the amount of soil organic C and root C.

The role of vegetation can gain soil organic C as carbon sink to the land through the biological production process. Thus forest protection and reforestation establishment are very important for carbon sequestration in terrestrial ecosystem. A significant C accumulation in soil will occur continually, if the reforestation is expanded to restore tree biomass on degraded land throughout the region. In addition, improved land use management practices could greatly increase soil C sequestration in the surrounding area. To practice the integrated techniques of land use management in different areas of Thailand, several land-use patterns are promptly coordinated adjacent to each other, which not help to raise economic benefits, but prevent soil erosion and land degradation. Appropriate land use management considerably reduces the emissions of carbon from the terrestrial ecosystem as well as conserves the carbon sink into the ecosystem. This study could confirm the important role of soil organic carbon fixing strategy in order to mitigate greenhouse gases especially carbon dioxide in the atmosphere.

CHAPTER V

CARBON STOCKS IN DIFFERENT LAND-USE TYPES

ABSTRACT

Land-use changes are associated with changes in land cover and carbon stocks. Since the 1970s, reforestation activities have been implemented in the Nam Yao sub-watershed, Thailand. Farmland and degraded forests were replaced with fruit orchards and forest plantations. The primary objectives of this study include determining carbon stocks in various forms and land-use types as well as to estimate the proportions of aboveground, litter carbon, soil organic and fine root carbon storage forms. This included primary forest, reforestation and agricultural land. The results of the study revealed that the amount of total carbon stock of hill evergreen forest and dry evergreen forest (398.43 ± 25.61 and 377.38 ± 14.74 Mg C ha^{-1}) was the greatest ($P < 0.05$). In the reforestation, total carbon stock of the 26-year-old reforestation was the greatest (205.67 ± 10.30 Mg C ha^{-1}) while total carbon stock of the 6-year-old fallow land was the greatest (120.21 ± 2.43 Mg C ha^{-1}) in the agricultural land. The differences in carbon stocks across land-use types are the primary consequence of variations in the vegetation biomass and the soil organic matter. These results indicate a relatively large proportion of the C loss is due to forest conversion to agricultural land. However, the C can be effectively recaptured through reforestation where high levels of C are stored in biomass as carbon sinks, facilitating carbon dioxide mitigation.

Key words: carbon stock, aboveground carbon, soil organic carbon, root carbon, land use

5.1 INTRODUCTION

Estimates of carbon stocks in tropical ecosystem are important to understand the global carbon cycle, formulation and evaluation of global priorities to reduce global warming, and the management of ecosystems for carbon sequestration purposes. In the tropics, estimates of carbon stocks focused on quantifying the aboveground component (Houghton, 2005). Although, the carbon stocks in aboveground forest biomass are reasonably well known as a result of continuous forest inventories (Goodale *et al*., 2002). Estimations of forest biomass are several problems in published estimates of C stocks from ground-based measurement i.e. uncertainty associated with spatially data, small inventory area (<1 ha), and incomplete measurements of all C pools (Houghton, 2005).

In forest ecosystem, carbon stock is a basic parameter of studying carbon exchange between forest and atmosphere. The carbon stocks in forests may change with a change in forest area. In many cases, losses of biomass associated without change in forest area such as forest fragmentation, and ground fires (Laurance *et al*., 2000; Barlow *et al*., 2003). In addition, forest conversion to agriculture results in the reduction of terrestrial carbon stocks. Accordingly, the conversion of forests to agricultural land not only reduces C stocks in vegetation but also causes significant losses of soil organic carbon (Post and Kwon, 2000). Reduction of soil C stocks are also associated with agricultural management i.e. residue removal via harvesting or burning, and soil tillage (Hairiah *et al*., 2001).

In Thailand, forest degradation has been identified as a major contributing factor to carbon stock losses. FAO (2003) estimated that Thailand’s annual forest loss was at 112 million hectares per year, during the period 1990-2000 (0.7% annually). Over the period 2000-2004, Thailand lost an average of 60,475 ha of natural forest per year (National Park, Wildlife and Plant Conservation Department, 2005). The deforestation rate has declined slightly since the period 1990-1995 due to already diminished forest cover as well s increasing public and governmental ecological interest (FAO, 2003). Estimates of Thailand’s CO_2 emission in 1994 were 241 Tg, and the projected level of CO_2 emissions in 2020 were approximately 583 Tg to 777 Tg. Total CO_2 emissions would continue to increase because of a more than two fold increase in energy consumption between the years 2000 and 2020. The average increase of CO_2 emission from the energy and forestry sectors is about 5% annually (OEPP, 2000).

Based on current information, reforestation is believed to have the potential to contribute to C storage directly through accumulation of C in biomass and soil (Silver *et al.*, 2000). Thus some of degraded land and agricultural land which is abandoned in Thailand is reforested either through natural succession or through assisted succession and plantation establishment. The secondary forests which typically results from these activities have a potential to accumulate carbon in biomass. However, carbon in growing and recovering vegetation are generally more difficult to detect with satellite data than changes in forest area and more difficult to document from census data. Generally, vegetation in land use is a major determinant of the vertical distribution of soil organic carbon (Jobbágy and Jackson, 2000). In previous research, Jackson *et al.*, (1996) examined above- and belowground allocation patterns and vertical root distributions for terrestrial biomes and plant functional types, showing differences among grass-, shrub-, and tree-dominated systems.

Due to a limitation in carbon stock in different land-use types in Thailand, total carbon stocks and their distribution are necessary to estimate and compare the relative carbon stocks in different land-use types. Estimation of carbon stocks in this study included above- and belowground, litter, coarse woody debris and soil carbon. The objectives of this study are: (i) to assess carbon stock in various forms in different land-use types; and (ii) to compare the relative C stocks between carbon pools for use in climate change mitigation.

5.2 METHODS

5.2.1 Study site

The study area is located in Nam Hean watershed management unit area, Num Yao sub-watershed, Nan province (19°05′10″N, 100°37′02″E). The land area is approximately 19,000 ha. The elevation ranges from 215 to 1,674 m a.s.l. The soil parent material consists of sandstone, shale stone and lime stone. Soils are mainly Red Yellow Podzolic soils and Reddish Brown Lateritic soils. The average air temperature is 16.9 °C during the dry season and 32.5 °C during the wet season. Average annual precipitation is 1,405 mm. The land cover types consist of hill evergreen and mixed deciduous forest, reforestation, orchard, cornfields, paddy fields, and small part of other crop cultivations. In this area, the natural forest has been severely degraded during the past thirty years due to legal and illegal logging, shifting agriculture, and uncontrolled forest fires. Because of the severe deterioration of the forest conditions, reforestation initiatives have become a high priority to the Royal Thai Government. Since the 1960s, reforestation activities have been implemented in the degraded areas of Nam Hean watershed. Farmland and heavily eroded areas were replanted with fruit and economic trees by hill tribes and Thais. In the late 1970s, plans to reforest depleted areas by planting native and exotic species for the purpose of watershed conservation were designed and implemented (Royal Forest Department, 1998).

The study was conducted in three main land-use types: forest, reforestation, and agricultural land. All five natural forest sites had been protected from logging for over half a century, three of which were hill evergreen forest, and two were mixed deciduous forests (Table 1). The reforested sites were planted with four native species and two exotic species in 1979 (Table 1). The agricultural sites were cleared prior to 1957 after which these areas were privately owned and cultivation of small grain and corn was practiced by illegal private owners. The agricultural sites included fallow land (6-year fallow), orchard (*Litchi chinensis*), paddy fields, and corn fields which still employ conventional tillage and chemical fertilizers (Table 5.1).

Table 5.1 Study sites in Nam Haen Watershed Management unit area

Sites	Location	Type/vegetation	Plot size (m^2)	Plot Number
Forest				
HEF	47Q 0672295 UTM 2126899	Hill evergreen forest	50 x 50	8
DEF	47Q 0672344 UTM 2125649	Dry evergreen forest	50 x 50	8
MDF	47Q 0675457 UTM 2118240	Mixed deciduous forest	50 x 50	8
CSF	47Q 0680732 UTM 2115809	Mixed deciduous forest	50 x 50	8
CMF	47Q 0685006 UTM 2116906	Mixed deciduous forest	50 x 50	8
Reforestation				
RF26	47Q 0684082 UTM 2122527	*Gmelina aborea* Roxb.	50 x 50	4
RF19	47Q 0680748 UTM 2119676	*Eucalyptus camaldulensis* Dehn. *Tectona grandis* Linn.	50 x 50	4
RF14	47Q 0683003 UTM 2122381	*Tectona grandis* Linn.	50 x 50	4
RF10	47Q 0679903 UTM 2119368	*Tectona grandis* Linn. *Pterocarpus macrocarpus* Kurz. *Afzelia xylocarpa* (Kurz) Craib. *Acacia catechu* (L.f.) Willd, and *Pyrus malus* L.	50 x50	4
RF9	47Q 0680990 UTM 2119752	*Tectona grandis* Linn. *Pterocarpus macrocarpus* Kurz. *Afzelia xylocarpa* (Kurz) Craib. *Acacia catechu* (L.f.) Willd, and *Bauhinia vriegata* L.	50 x 50	4
Agriculture				
FL	47Q 0683820 UTM 2123305	Fallow land (5-6 years)	50 x 50	4
LT	47Q 0673679 UTM 2126388	*Litchi chinensis* Sonn. spp.	50 x50	4
Rice	47Q 0681248 UTM 2117440	*Oryza sativa* Linn.	1 x 1	10
Corn1	47Q 0673788 UTM 2126210	*Zea mays* Linn.	1 x 1	10
Corn2	47Q 0681215 UTM 2124023	*Zea mays* Linn.	1 x1	10

5.2.2 Aboveground carbon and carbon stocks

To assess the biomass, plots of 50 x 50 m^2 were established in all land-use types. The number of plots chosen for each land-use type was based on its distribution in the study area and the expected variability in the amount of carbon. In the forest, the most common type of hill evergreen and mixed deciduous areas were expected to have a high degree of variability in the amount of carbon thus a larger number of plots (n = 32) were selected. Reforested areas, were expected to have lower variability in the amount of carbon, and fewer plots (n = 20) were chosen. For agricultural land, the selected plots were located in various fields (n = 28). In fallow land and orchards, selected plots of 50 x 50 m^2 were established (n = 8). Corn fields and paddy fields were selected with the plots size of 1 x 1 m^2 (n = 30). All individual trees of ≥ 4.5 cm diameter at breast height (dbh) at 1.30 m height above the ground were measured and identified. Density (individual ha^{-1}), basal area (m^2 ha^{-1}) and biomass (Mg ha^{-1}) were calculated. The aboveground biomass was calculated using the developed allometric equations in Thailand for hill evergreen forest (Tsutsumi *et al*., 1983), mixed deciduous forest (Ogawa *et al*., 1965), *Gmelina aborea* Roxb. (Sritulanont *et al*., 1983) *Eucalyptus camaldulensis* Dehn. (Kamo, 1999), *Tectona grandis* Linn. (Viriyabuncha *et al*., 2001), and Bamboo (*Thyrsostchys siamensis*, Suwannapinunt, 1983; *Gigantchloa albociliata* and *Bambusa tulda*, Kutintara *et al*., 1995). We developed the following equations for *Litchi chinensis* tree at the site (see chapter III).

The biomass of the understory layer consisting of <4.5 cm diameter trees (saplings) were analyzed in the 25 sub plots of 4 x 4 m^2 in each plot of 50 x 50 m^2. Seeding and herbs were analyzed in the 25 sub plots of 1 x 1 m^2 in each sapling plot in forest, reforestation, fallow land, and orchards. Mean wet weight was obtained from each species by measuring wet weight of individuals. Sub-samples were oven-dried to determine the ratio of dry/wet weight. The ratios were then applied over the entire sample of each species for conversion to dry weight. All aboveground components were assumed to have 50% C content (Brown and Lugo,1984; Levine *et al*., 1995).

5.2.3 Root carbon and soil carbon stocks

The soil samples were collected consisting of five random samples in each 50 x 50 m^2 plot across land-use types. The number of soil samples in forest, reforestation and agricultural land was 160, 100 and 115, respectively. The soil was sampled by soil cores, hereafter referred to as soil profiles, to a depth of 100 cm and separated into layers 0-20, 20-40, 40-60, 60-80, and 80-100 cm. In order to detect the soil organic carbon (SOC) storage change without destroying soil structure, soils bulk density was measured by using a cutting ring. Organic carbon content in soil was determined based on three replicates using the Walkley-Black method (Walkley and Black, 1934). This method oxidizes only the organic carbon while avoiding interference by carbonates (Hesse, 1971). The SOC content of each layer was calculated for bulk density and summed for the entire soil profile to estimate total SOC content.

The cores were sub-sampled for fine roots at 0-20, 20-40, 40-60, 60-80 and 80-100 cm depth intervals. Fine roots size $\leq$ 5 mm in diameter were separated by hand sorting and then successively sieved with a 2 and 1 mm mesh sieve to remove the remaining root fragments from soil in each layer. The pit (15 cm x 15 cm) was dug to collected coarse roots (>5 mm in diameter) samples. Coarse roots were separated from soil by hand. No species-wise classification of all roots was attempted. Each sampling washed and air-dried. The live and dead roots were weighed and then oven-dried at temperature of 70 °C for 24h to constant weight. Root materials were ground to a powder and carbon contents in root were analyzed using a CN Corder. The amounts of carbon of each sample were determined by multiplying dry weights of sample. The distribution of root carbon (RC) in each profile was calculated from the soil confined to a depth of 100 cm.

5.2.4 Aboveground litter carbon

Aboveground litter is comprised of litter standing (leaf, twigs and fine woody materials) and coarse woody debris (>2 cm diameter). In each plot of 50 x 50 m^2, litter samples were collected in the nine sub plots of 1 x 1 m^2 and place in paper bags. Aboveground litter was oven dried at 55 °C to constant weight and sorted into litter classes. In each plot of 50 x 50 m^2, coarse woody debris was measured in one plot of 10 x 10 m^2. The material was weighed and sample of at least 10% of the total fresh weight in the plot was collected to estimate dry weight in the laboratory. The sub-samples were ground to a fine powder in a grinding machine. Each of these was then weighed and rolled in tin cups for carbon analysis by using dry combustion methods. Sum of carbon in each litter class was computed for stocks of aboveground litter carbon.

5.3 CALCULATIONS

Total basal area was calculated for every plot in units of m^2 ha^{-1} summing up the basal area of each tree and extrapolating to a hectare.

Total C stock (TCS) was estimated by aggregating the mean amount of carbon in different pools (total aboveground vegetation carbon (TAGC), total litter carbon (TLC), total root carbon (TRC), and soil organic carbon (TSOC)):

$$TCS = TAGC + TLC + TBGC + TSOC \qquad \text{(equation 5.1)}$$

TAGC was obtained as the sum of the amount of carbon in the aboveground carbon pools (aboveground carbon of trees ≥4.5 cm in diameter; TC), aboveground carbon of sapling (trees less than 4.5 cm in DBH but taller than 1.30 m in height; SPC), aboveground carbon of seedlings (trees less than 4.5 cm in DBH and below 1.30 m in height; SDC), aboveground carbon in understory layer (Herbs and grasses; USC), and aboveground carbon of bamboo; BC:

$$TAGC = TC + SPC + SDC + USC + BC \qquad \text{(equation 5.2)}$$

TLC was obtained as the sum of the amount of aboveground litter carbon (leaf, twigs and fine woody materials; L) and coarse woody debris carbon (>2 cm diameter; WD):

$$TLC = LC + WDC \qquad \text{(equation 5.3)}$$

TBGC is composed of the fine root carbon (≤5 mm in diameter; FRC) and coarse root carbon (>5 mm in diameter; CRC):

$$TBGC = FRC + CRC \qquad \text{(equation 5.4)}$$

TSOC was obtained by combining the data of soil bulk density and % carbon content in soil down to 1 m depth.

5.4 STATISTICAL ANALYSIS

Differences in aboveground carbon, litter and coarse woody debris carbon in each land-use type and between land-use types were analyzed using a One-way Analysis of Variance (within subject and between subjects). Post-hoc multiple comparison method was used to compare a difference between and within treatments.

5.5 RESULTS AND DISCUSSION

5.5.1 Carbon estimations

Total carbon stocks (TCS) tended to increase within the forest and to be lower in the reforestation and the fallow land (Table 5.2). TCS was the greatest in the hill evergreen forest (398.43 ± 25.16 Mg C ha^{-1}) while TAGC in the two sites of corn field were the lowest (83.35 ± 1.23 and 87.86 ± 1.05 Mg C ha^{-1}) ($P < 0.05$). Soil organic carbon (SOC) was the main fraction of TCS (56-64% for the forest, 73-85% for the reforestation and 92-94% for the agricultural land, respectively) in all land-use types. Total aboveground vegetation carbon (TAGC) represented a minor fraction of TCS (29-38% for the forest, 9-20% for the reforestation and 2-7% for the agricultural land, respectively). Total root carbon (TRC) was a small fraction of TCS, which was dominated by coarse root carbon (CRC). In contrast, all belowground carbon in rice paddy fields and corn fields are composed of only FRC. CRC in the forest and the reforestation were accounted for 3-4% of TCS, while CRC was 0.45% for the agricultural land especially in only the fallow land and orchard field. Overall, FRC fraction of TCS was accounted for lower than 2%.

Comparison between the forest and the reforestation, the ratios between TAGC and TRC was lower in the forest than in the reforestation. The results suggest that the belowground limitations are strongly higher in the reforestation as secondary forest than in the primary forest. Total litter carbon (TLC) was a very small fraction of TCS, litter carbon (LC) fraction varied between 0.02 - 1.24%. Coarse woody debris carbon (CWC) represented lower than 1% in all land-use types.

Table 5.2 Total carbon stock (Mg C ha^{-1}) in different land-use types

Land-use type	Aboveground vegetation carbon	% of total	Litter carbon	% of total	Coarse woody debris	% of total	Fine root carbon	% of total	Coarse root carbon	% of total	Soil organic carbon	% of total	Total carbon stock	% of total
HEF	150.07 ± 12.58 a	37.67	3.69 ± 0.03 b	0.93	3.17 ± 0.17 b	0.80	4.74 ± 0.10 a	1.19	14.82 ± 0.10 a	3.72	221.94 ± 1.66 a	55.70	398.43 ± 25.16 a	100.00
DEF	138.88 ± 13.39 a	36.80	4.20 ± 0.05 a	1.11	3.70 ± 0.21 a	0.98	4.15 ± 0.06 b	1.10	12.16 ± 0.06 b	3.22	214.29 ± 1.97 b	56.78	377.38 ± 14.74 a	100.00
MDF	83.30 ± 7.64 b	29.28	2.16 ± 0.02 e	0.76	1.54 ± 0.11 c	0.54	3.80 ± 0.04 c	1.34	11.97 ± 0.04 c	4.21	181.76 ± 2.46 c	63.88	284.53 ± 10.03 b	100.00
CSF	95.17 ± 5.15 b	34.40	1.98 ± 0.02 f	0.72	1.59 ± 0.14 c	0.56	3.68 ± 0.04 e	1.33	10.36 ± 0.04 e	3.74	163.91 ± 4.90 e	59.24	276.69 ± 10.02 b	100.00
CMF	78.63 ± 8.54 b	29.28	2.18 ± 0.03 d	0.81	1.50 ± 0.11 c	0.37	3.75 ± 0.04 d	1.40	10.98 ± 0.04 d	4.09	171.54 ± 2.97 d	63.87	268.58 ± 11.13 b	100.00
RF26	40.70 ± 6.36 c	19.79	1.46 ± 0.03 h	0.71	0.76 ± 0.10 e	0.31	3.62 ± 0.03 f	1.76	7.52 ± 0.15 f	3.66	151.61 ± 3.66 f	73.72	205.67 ± 10.33 c	100.00
RF19	15.69 ± 1.63 de	9.43	0.99 ± 0.02 i	0.60	0.51 ± 0.06 g	0.35	3.22 ± 0.02 h	1.94	6.16 ± 0.24 h	3.70	139.73 ± 1.80 h	84.02	166.30 ± 3.77 d	100.00
RF14	24.95 ± 2.64 cd	12.82	2.41 ± 0.03 c	1.24	0.68 ± 0.06 f	0.45	3.58 ± 0.03 g	1.84	7.23 ± 0.25 g	3.71	155.79 ± 3.35 f	80.04	194.67 ± 5.64 c	100.00
RF10	36.55 ± 7.30 cd	18.59	1.73 ± 0.02 g	0.88	0.88 ± 0.08 d	0.24	3.65 ± 0.02 ef	1.86	7.13 ± 0.21 g	3.63	146.44 ± 4.51 g	74.60	196.38 ± 11.54 c	100.00
RF9	14.29 ± 1.98 de	8.68	0.74 ± 0.02 j	0.45	0.39 ± 0.02 h	0.04	2.64 ± 0.02 i	1.60	6.08 ± 0.02 h	3.69	140.57 ± 4.54 h	85.34	164.71 ± 5.86 d	100.00
FL	5.91 ± 1.21 ef	4.92	0.10 ± 0.01 k	0.08	0.05 ± 0.01 i	0.00	0.47 ± 0.04 l	0.39	0.54 ± 0.06 i	0.45	113.14 ± 2.26 i	94.12	120.21 ± 2.43 e	100.00
Litchi	8.15 ± 0.75 e	7.41	0.02 ± 0.01 l	0.02	0.00 ± 0.00 j	0.00	0.55 ± 0.03 k	0.50	0.49 ± 0.05 i	0.45	100.79 ± 1.97 k	91.63	110.00 ± 3.14 f	100.00
Rice	2.49 ± 0.11 g	2.32	0.00 ± 0.00 m	0.00	0.00 ± 0.00 j	0.00	0.47 ± 0.06 l	0.44	0.00 ± 0.00 j	0.00	104.58 ± 0.99 j	97.25	107.54 ± 0.99 g	100.00
Corn1	4.82 ± 0.46 f	5.78	0.00 ± 0.00 m	0.00	0.00 ± 0.00 j	0.00	0.96 ± 0.05 j	1.15	0.00 ± 0.00 j	0.00	77.57 ± 1.38 m	93.07	83.35 ± 1.23 h	100.00
Corn2	4.96 ± 0.33 f	5.65	0.00 ± 0.00 m	0.00	0.00 ± 0.00 j	0.00	1.00 ± 0.06 j	1.14	0.00 ± 0.00 j	0.00	81.90 ± 1.56 l	93.22	87.86 ± 1.05 h	100.00

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

For all C pools, although LC in the 14-year-old reforestation was higher than LC in all mixed deciduous forests. The other pools (TAGC, LC, CWC, FRC, CRC and SOC) were different between the forest and the reforestation, in which were colossal due to the human disturbances. Comparison between the reforestation and the agricultural land, TAGC in the 6-year-old fallow land and orchard field of *L. chinensis* were not significant with TAGC in the 19- and 9-year-old reforestation. But for other pools (LC, CWC, FRC, CRC and SOC) in the reforestation were higher than in the agricultural land ($P < 0.05$). All data show that all C pools are more active to C losses associated with land-use changes.

Carbon estimation of TCS (sum of aboveground and belowground carbon and soil organic carbon) in the evergreen forests in this study was similar to that found in primary forest (283.70 ± 55.50 Mg C ha^{-1}) while TCS in the reforestation was lower than that in the secondary forest (228.20 ± 13.10 Mg C ha^{-1}) in Porce region, Colombia (Sierra *et al*., 2007). Although these estimates are difference in soil depth (4 m depth) and different C pools (including snags and necromass). Moreover, coarse root carbon in Colombia was measured with an allometric equation, our estimate was also in the range for Colombia.

In case of TCS (sum of aboveground carbon and soil organic carbon at 20 cm depth) in the forest (127.33-218.12 Mg C ha^{-1}) and the reforestation (57.74-98.51 Mg C ha^{-1}) in this study are much higher than the studied in Dry Chaco, Argentina (64.96 Mg C ha^{-1} for primary forest and 36.48 Mg C ha^{-1} for secondary forest; Bonino, 2006). This may be depending on different factors such as climate, plant community and soil properties. Moreover, the above difference may be due to the higher rainfall that characterized in the study area as compared with Dry Chaco (1,405 mm and 450mm, respectively). Therefore, arid and semiarid lands deserve special attention when discussing global carbon cycle if drastic biomass losses (Bonino, 2006).

On the other hand, TCS (sum of aboveground carbon, fine root carbon (≤ 5 mm in diameter) and soil organic carbon at 1 m depth) in the forest (253.92-376.75 Mg C ha^{-1}), the reforestation (157.50-195.93 Mg C ha^{-1}) and the agricultural land (83.35-119.52 Mg C ha^{-1}) in this study are comparable and in the range of study in Chipas highland, Mexico (540.70 for Oak-evergreen cloud forest, 385.60 Mg C ha^{-1} for fragmented forest, 224.00 Mg C ha^{-1} for Pine and Pine-Oak forest and 151.20 Mg C ha^{-1} for cultivated and pasture, respectively, Mendoza-Vega *et al*., 2003).

Ratios between carbon pools were calculated (Table 5.3, Appendix 14). These ratios represented C fractions between different pools and can be used to estimate the proportion of C stored in different ecosystem pools as well. C stored in TAGC was about five to nine times higher than TBGC in the forest, while C stored in TAGC was about two to four times higher than in TBGC in the reforestation. In the agricultural land, C stored in TAGC was about five to eight times higher than TBGC. For SOC, organic C in soil was about eleven to thirteen times higher than TBGC in the forest, while SOC in soil was about fourteen to sixteen times higher than TBGC in the reforestation. Comparison to other land-use types, ratios between SOC and TBGC in agricultural land was higher than that in the forest and the reforestation. SOC was about eighty-one to two hundred and twenty two times higher than TBGC. In the internal comparison of the average ratio between TAGC : TBGC : SOC in the forest, the reforestation and the agricultural land were 7: 1 : 12; 3 : 1 : 14; and 6 : 1 : 106, respectively (Table 5.4).

Table 5.3 Ratios between total aboveground carbon : total belowground carbon : soil organic carbon in different land-use types

Land - use type	Vegetation carbon*	Litter carbon *	Coarse woody debris*	Total aboveground carbon* (TAGC)	Fine root carbon *	Coarse root carbon *	Total belowground carbon* (TBGC)	Soil organic carbon * (SOC)	**Ratio TAGC:TBGC:SOC**
HEF	150.07	3.69	3.17	156.93	4.74	14.82	19.56	221.94	**8 : 1 : 11**
DEF	138.88	4.20	3.70	146.78	4.15	12.16	16.31	214.29	**9 : 1 : 13**
MDF	83.30	2.16	1.54	87.00	3.80	11.97	15.77	181.76	**5 : 1 : 11**
CSF	95.17	1.98	1.59	98.74	3.68	10.36	14.04	163.91	**7 : 1 : 12**
CMF	78.63	2.18	1.50	82.31	3.75	10.98	14.73	171.54	**6 : 1 : 12**
RF26	40.70	1.46	0.76	42.92	3.62	7.52	11.14	151.61	**4 : 1 : 14**
RF19	15.69	0.99	0.51	17.19	3.22	6.16	9.82	139.73	**2 : 1 : 14**
RF14	24.95	2.41	0.68	28.04	3.58	7.23	10.81	155.79	**3 : 1 : 14**
RF10	36.55	1.73	0.88	39.16	3.65	7.13	10.78	146.44	**4 : 1 : 14**
RF9	14.29	0.74	0.39	15.42	2.64	6.08	8.72	140.57	**2 : 1 : 16**
FL	5.91	0.10	0.05	6.06	0.47	0.54	1.01	113.14	**6 : 1 : 112**
Litchi	8.15	0.02	0.00	8.17	0.55	0.49	1.04	100.79	**8 : 1 : 97**
Rice	2.49	0.00	0.00	2.49	0.47	0.00	0.47	104.58	**5 : 1 : 222**
Corn1	4.82	0.00	0.00	4.82	0.96	0.00	0.96	77.57	**5 : 1 : 81**
Corn2	4.96	0.00	0.00	4.96	1.00	0.00	1.00	81.90	**5 : 1 : 82**

Remark: * The unit in each pool is Mg C ha^{-1}

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

Table 5.4 Internal comparison of the average ratio between total aboveground carbon : total belowground carbon : soil organic carbon in forest, reforestation and agricultural land

Land-use type	Total aboveground carbon* (TAGC)	Total belowground carbon* (TBGC)	Soil organic carbon* (SOC)	**Ratio TAGC:TBGC:SOC**
Forest	114.35	16.08	190.69	**7 : 1 : 12**
Reforestation	28.55	10.25	146.83	**3 : 1 : 14**
Agricultural land	5.30	0.90	95.60	**6 : 1 : 106**

* The unit in each pool is Mg C ha^{-1}

Changes TCS are associated with shifts in land-use and/or land management practices. The estimates of TCS varied greatly over land-use types in this study. The greatest TCS loss overall occurred in the agricultural land, with the major contribution in TAGC. The result showed that a large variation of carbon pools in different land-use types. The TAGC, TBGC and SOC are sequestered highest in the forest and decreased in the reforestation and the agricultural land significantly due to the different biomass production. It suggested that conversion of the forest to agricultural land, the C loss from aboveground biomass will be greater than other carbon pools. SOC content was found to be larger than TAGC content over the land-use types. SOC showed the least drastic changes among them. The data indicated that the TAGC pool is highly responsive to land-use changes while the SOC is more resistant than other pools. However, it can be concluded that the SOC accumulates more slowly than TAGC. The slow SOC turnover rates, as compared to aboveground vegetation, suggests that soil C level does not react as quickly to change in land use (see also Walker and Desanker, 2004). Growing vegetations tend to maintain SOC level by continuously supplying C from root turnover when compared with bare land, which tends to deplete C (Sanchez *et al*., 2002).

5.5.2 Effects of land use

For the area of the study (19,000 ha), the forest, the reforestation and the agricultural land cover a large proportion of total area (20%, 23% and 47%, respectively). Given our results, the average of TCS in the forest, the reforestation and agricultural land were 321.12 ± 19.08 Mg C ha^{-1}, 185.55 ± 8.16 Mg C ha^{-1} and 101.79 ± 2.13 Mg C ha^{-1}, respectively. The total amount of carbon stored in the forest

(1220.26 Gg) was higher than in the agricultural land (908.98 Gg) and the reforestation (810.85 Gg) (Table 5.5). However, in terms of the relation of each land-use type to TCS in area, the agricultural land contained nearly the same proportion as the reforestation. It is important to note that the pattern of land-use change in this area was driven directly by the agricultural practice and it is represented the other land-use change processes more common in this country. The conversion of agricultural land and degraded area to reforestation in this study was the result of conservation and restoration policy by National Park, Wildlife and Plant Conservation Department, Ministry of Natural Resources and Environment, Thailand.

Table 5.5 Average total carbon stocks in different land-use types in Nam Yao sub-watershed

Land- use type	Area of the study (Ha)	Total carbon stock (Gg C)
Forest	3,800.00	1,220.26
Reforestation	4,370.00	810.85
Agricultural land	8,930.00	908.98

5.6 CONCLUSION

The ratios between C pools in this study were an integrated estimation of the different C pools. Although this ratio was primary defined at the level of land-use type, it covered all main land-use types in the study area and northern region. Therefore, our results will help to accurately estimate the changes in each C pool associated with land-use dynamics. Deforestation and changes in land use cause of severe losses in the carbon stocks in Nam Yao sub-watershed, which has been prove for the Nam Haen Watershed Management Unit area. The greatest loss has occurred at aboveground biomass level, with a limit decrease of soil organic carbon content with respect to vegetation degradation. As the reforestation continue to be established all throughout the Nam Yao Sub-watershed, a significant total carbon sequestering will continue to occur potentially. In contrast, a consequence of the agricultural expansion obviously causes a significant deterioration in total carbon stock as carbon loss from terrestrial system to the atmosphere. Therefore, it is clear that the way to conserve the natural forest as well as to enhance and expand the reforestation area would be one solution of greenhouse gases mitigation and reduction by promoting carbon sink in both live biomass and soil organic carbon.

CHAPTER VI

CONCLUSIONS

The goals of this study were to estimate the carbon stocks and relative of carbon pools in different land-use types including natural forest ecosystems, reforestations and agricultural lands. Forest systems consist of foliage, branches and stems aboveground, and the belowground components of coarse and fine roots and associated symbionts. Trees vary in the allocation of carbon (C) and nutrients across the above- and belowground components in response to growing conditions. For forest managers maximizing C in the stem is important as this relates directly to the economic return from timber. Even, Thailand already banned the timber concession from natural forest for decades, the reforestations and forest plantations clearly become one of major concerns of the government in order to produce timber to supply domestic needs as well as to store carbon in terrestrial system contributing to greenhouse gases mitigation.

For aboveground carbon, several allometric relationships to estimate biomass are available from the literatures. In this study, the different allometric equations have been developed and used to estimate the biomass of forest and reforestation. The most robust estimate was given by finding the average of them. Regarding to the allometric equations-used are quite different, and each was collected by using a sample of trees in a specific locality and in different vegetation types, then the results vary greatly. The present technique of taking the average of each ecosystem as the best estimate has probably yielded the most reliable and cost-effective method of estimating biomass and aboveground carbon in this situation.

The allocation of C belowground is intimately linked with whole tree or stand C allocation dynamics. Forest growth and the allocation of C belowground are influenced by a variety of environmental and plant related factors (e.g. genetics, age). The mechanistic understanding of fine and coarse root systems has not yet well developed to a stage where root biomass and turnover can be accurately estimated or modeled in forest systems. Generally, allocation of C to fine roots is greater on drier or nutritionally poor sites, and live root mass might be a shorter live in water or nutrient stressed systems. However, the existing of insufficient data do not allow the confidential estimate, it is necessary for conducting more studies to answer different complicated mechanism in bio-physico-chemical interactions of belowground carbon allocation. For instance, the allocation of C to root systems also needs to be understood in the context of the C balance of the whole stand. The overall productive capacity of a system is a key driver of root activity, and productivity is naturally influenced by species, site fertility and climate. The net effect of climate change on forest productivity needs to be better understood so that adaptive and effective management can be adopted. However, the impacts of the enhanced greenhouse effect on forest ecosystems are not easily investigated, and the feedback mechanisms relating to belowground productivity even need to be better understood.

In the reforestation, there is a change in species composition in the planting design compared with natural forest dominated. Normally, the reforestation system often designs to plant mono- or multi- non-native fast growing species for commercial purpose, but just recently the concept of reforestation really adopts the way to imitate natural forest ecosystem by planting dominant native species. Therefore, reforestation systems can contribute to increase short-term carbon sequestration because of their carbon storage potential in both above and belowground. In this regard, the use of multi-purpose plant species can be useful, it may involve food crops as a diversified agro-forestry concept and the system can be socially accepted. Moreover, reforestation also improves soil fertility and stores organic carbon in forms of both live biomass and soil over times.

For soil organic carbon (SOC), SOC accumulation is a function of organic matter input rate and soil organic matter mineralization rate. The climate and vegetation are driving forces in this process while topography and soil type may transform the rate of the processes and hence the magnitude of soil organic matter accumulation. Changes in SOC caused by land use and/or land cover changes (LU/LC changes) are linked to a change in vegetation cover that transform the litter input rate, and changes in soil organic matter mineralization rate due to soil disturbance. The complicated interaction of the above factors also associated with determining the SOC content in the soil. This makes a difficulty to examine changes in amount of soil organic carbon regarding LU/LC changes.

In this study, there were significantly differences in amounts of SOC between land-use types. The effect of land-use change in this study showed high probability values. The agricultural land had SOC content lower than that of the forest and the reforestation, 20 to nearly 60% lower, depending on the vegetation type. The internal comparison of the average ratio of aboveground, belowground carbon and soil organic carbon (TAGC : TBGC : SOC), in each different land-use types was 7:1:12, 3:1:14 and 6:1:106 for the forest, the reforestation and the agricultural land, respectively. In conclusion, the reforestation provides a high potential in carbon sequestration into terrestrial system due to growing process while the natural forest is storing carbon in both above and belowground forms with limited increasing carbon sequestration in live forms. Therefore, it is possible and effective to enhance the reforestation in degraded or disturbed lands, which the reforestation system can directly absorb carbon dioxide from atmosphere and fix into live biomass even mobilize to soil system. To protect and solve the global warming problem, it is very important to protect natural forest ecosystems as well as restore the degraded forest by the reforestation, which will possibly safe and vital our planet from the greenhouse effects.

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APPENDICES

APPENDIX A

STUDY DATA

Appendix 1 Biomass equation in this study

Equation for evergreen forest (Tsutsumi *et al.*,1983)

$Ws = 0.0509*(D^2H)^{0.919}$ (Equation 3.1)
$Wb = 0.00893*(D^2H)^{0.977}$
$Wl = 0.0140*(D^2H)^{0.669}$

Equation for mixed deciduous forest (Ogawa *et al.*, 1965)

$Ws = 0.0396*(D^2H)^{0.9326}$ (Equation 3.2)
$Wb = 0.003487*(D^2H)^{1.027}$
$Wl = 1/[(28.0/(WS+WB))+0.025]$

Equation for *Gmelina aborea* Roxb. (Sritulanont *et al.*, 1983)

$\text{Log } Ws = 0.8431 \log D^2H - 1.287$ $r^2 = 0.8390$
$\text{Log } Wb = 1.798 \log D^2H - 0.238$ $r^2 = 0.9880$
$\text{Log } Wl = 1.888 \log D^2H - 6.836$ $r^2 = 0.9970$
(Equation 3.3)

Equation for *Eucalyptus camaldulensis* Dehn. (Kamo, 1999)

$\text{Log } Ws = 0.0448*(D^2H)^{0.9108}$ $r^2 = 0.9608$
$\text{Log } Wb = 0.0004*(D^2H)^{1.2477}$ $r^2 = 0.9263$
$\text{Log } Wl = 0.0003*(D^2H)^{1.0744}$ $r^2 = 0.5176$
(Equation 3.4)

Equation for *Tectona grandis* Linn. (Viriyabuncha *et al.*, 2001)

$Ws = 0.0271\ D^2H^{\ 0.9435}$ $r^2 = 0.9915$
$Wb = 0.0013\ D^2H^{\ 1.1339}$ $r^2 = 0.9304$
$Wl = 0.0205\ D^2H^{\ 0.6850}$ $r^2 = 0.8090$
(Equation 3.5)

$AGB = Ws+Wb+Wl$ (Equation 3.6)

Appendix 1 Biomass equation in this study (continued)

Equation for (*Cephlostachyum pergracile* Munro, *C. virgatum* Kurz., and *Gigantchloa albociliata* Munro, Kutintara *et al*. 1995).

Cephlostachyum pergracile Munro, *C. virgatum* Kurz.,

$$Wt = 0.17446*(D^2)^{1.0437} \qquad \text{(Equation 3.7)}$$

and *Gigantchloa albociliata* Munro

$$Wt = 0.2425*(D^2)^{1.0751}$$

(Equation 3.8)

Where AGB = Aboveground biomass (kg per tree)
Ws = Stem dry weight (kg per individual tree)
Wb = Branch dry weight (kg per individual tree)
Wl = Leave dry weight (kg per individual tree)
Wt = Aboveground biomass of bamboo (kg per tree)
D = Diameter at breast height (cm)
H = Height of tree (m)

For *Litchi chinensis*, dry weight was calculated as follows:

$$DWw \quad \frac{DWs}{FWs} \bullet FWw \qquad \text{(Equation 3.9)}$$

where DWw = Whole dry weight
DWs = Dry weight of sample
FWw = Whole fresh weight
FWS = Fresh weight of sample

Appendix 2 Vegetation analysis

Vegetation data were analyzed for quantitative ecological parameters as follows:

Basal area of each tree following equation

$$\text{BA} = (0.00007854)dbh^2 \qquad \text{(Equation 3.10)}$$

Relative Density

$$\text{RD} = \frac{n_i}{N} \times 100 \qquad \text{(Equation 3.11)}$$

Relative Frequency

$$RF = \left(\frac{f_i}{\sum_{i=1}^{s} f_i} \right) \times 100 \qquad \text{(Equation 3.12)}$$

Relative dominance

$$RD = \left(\frac{\sum_{i} BA_i}{\sum_{i=1}^{s} BA_i} \right) \times 100 \qquad \text{(Equation 3.13)}$$

Importance Value Index

$$IVI = RD + RF + RD \qquad \text{(Equation 3.14)}$$

Where n_i = Number of individual of families *i*

N = Number of individuals of all families.

f = Frequency of species *i* (number of plots which families *i* occurance)

BAi = Basal area of families *i*

Appendix 2 Vegetation analysis (continued)

Families diversity

$$H' = -\sum_{i=1}^{S} (pi)(\log_2 pi) \qquad \text{(Equation 3.15)}$$

Where H′ = Index of families diversity

S = Families number in the sample

pi = Proportional abundance of the i th families (ni/N)

Appendix 3 Density, basal area, height and aboveground biomass of study sites.

Land use type	Plot	Density (stem ha^{-1})	Basal area (m^2 ha^{-1})	Average DBH (cm)	DBH (Min.) (cm)	DBH (Max.) (cm)	Average height (m)	Height (Min.) (m)	Height (Max.) (m)	Aboveground biomass Mg ha^{-1}
HEF	1	604.00	38.89	29.69 ± 18.65	8.40	103.78	17.39 ± 4.61	7.97	27.14	332.64
HEF	2	568.00	31.76	20.86 ± 16.69	5.99	95.80	15.26 ± 4.99	7.83	24.94	265.07
HEF	3	532.00	34.55	19.66 ± 15.84	5.34	104.24	14.83 ± 4.96	6.24	26.75	286.49
HEF	4	556.00	35.66	22.63 ± 17.51	5.12	92.09	15.83 ± 5.28	6.15	25.83	300.00
HEF	5	608.00	36.60	21.68 ± 17.27	4.84	109.77	15.66 ± 4.80	5.50	26.82	306.01
HEF	6	638.00	30.59	19.85 ± 15.09	5.23	86.56	15.04 ± 4.84	5.95	24.65	253.18
HEF	7	624.00	33.53	20.99 ± 15.65	5.24	82.79	15.45 ± 4.91	7.00	25.52	279.37
HEF	8	606.00	35.14	19.85 ± 16.90	4.68	86.69	15.56 ± 5.26	5.19	25.66	294.02
Average		592.00 ± 36.27	34.59 ± 2.65	21.90 ± 3.31	5.61 ± 1.19	95.22 ± 9.85	15.63 ± 0.78	6.48 ± 1.03	25.91 ± 0.91	289.60 ± 24.76
DEF	1	438.00	44.99	26.53 ± 23.79	4.52	162.22	16.94 ± 5.86	5.08	28.01	349.35
DEF	2	488.00	30.40	24.80 ± 20.31	4.50	133.50	16.38 ± 6.68	5.07	27.18	277.20
DEF	3	500.00	31.16	17.78 ± 16.94	4.58	152.21	13.48 ± 5.93	5.11	27.91	262.05
DEF	4	536.00	25.16	17.97 ± 16.09	4.75	97.65	14.61 ± 5.73	6.25	25.89	238.57
DEF	5	556.00	27.95	18.18 ± 17.01	4.86	106.78	14.63 ± 5.48	5.52	26.21	229.94
DEF	6	560.00	32.59	19.30 ± 19.27	4.70	106.30	14.60 ± 5.99	5.31	25.20	274.75
DEF	7	514.00	29.16	18.73 ± 18.27	4.77	111.16	14.76 ± 5.66	6.00	25.52	236.46
DEF	8	482.00	33.75	17.94 ± 19.57	4.55	113.65	13.79 ± 6.06	5.19	26.36	278.26
Average		509.25 ± 41.15	31.90 ± 5.94	20.15 ± 3.47	4.65 ± 0.13	122.93 ± 23.65	14.90 ± 1.19	5.44 ± 0.45	26.54 ± 1.06	268.32 ± 38.17
MDF	1	796.00	25.69	16.12 ± 12.32	4.55	60.66	14.01 ± 4.92	4.93	23.64	170.03
MDF	2	680.00	22.34	17.09 ± 11.27	4.70	66.61	14.84 ± 4.34	5.02	24.01	145.69
MDF	3	808.00	21.58	15.19 ± 10.49	4.53	59.88	13.90 ± 4.36	4.91	22.83	138.03
MDF	4	716.00	22.06	15.76 ± 12.02	4.71	72.01	13.94 ± 4.66	5.12	24.45	145.24
MDF	5	816.00	26.00	16.20 ± 12.00	4.64	59.61	14.21 ± 4.57	5.73	22.27	171.34
MDF	6	764.00	20.65	15.66 ± 9.87	4.98	58.77	14.30 ± 4.08	5.64	22.34	130.73
MDF	7	684.00	21.93	15.81 ± 12.61	4.63	58.31	13.90 ± 4.61	5.93	22.26	146.03
MDF	8	792.00	24.08	15.08 ± 12.67	4.57	68.85	13.52 ± 4.55	4.96	24.02	160.61
Average		757 ± 55.83	23.04 ± 1.98	15.86 ± 0.63	4.66 ± 0.14	63.09 ± 5.28	14.08 ± 0.39	5.48 ± 0.42	23.23 ± 0.90	150.96 ± 14.80

.

Appendix 3 Density, basal area, height and aboveground biomass of study sites (continued).

Land use type	Plot	Density (stem ha^{-1})	Basal area (m^2 ha^{-1})	Average DBH (cm)	DBH (Min.) (cm)	DBH (Max.) (cm)	Average height (m)	Height (Min.) (m)	Height (Max.) (m)	Aboveground biomass Mg ha^{-1}
CSF	1	800.00	24.97	16.04 ± 15.90	4.89	59.65	13.57 ± 6.03	4.85	23.40	175.00
CSF	2	791.00	24.47	14.63 ± 12.04	5.25	73.86	12.34 ± 5.12	5.61	24.48	172.64
CSF	3	808.00	26.28	15.89 ± 14.55	4.74	100.35	14.20 ± 5.81	5.10	25.34	194.98
CSF	4	824.00	26.75	15.20 ± 13.42	4.52	87.09	13.23 ± 5.94	4.78	24.97	182.42
Average		805.75 ± 14.01	25.62 ± 1.07	15.44 ± 0.65	4.85 ± 0.31	80.24 ± 17.47	13.34 ± 0.78	5.09 ± 0.38	24.55 ± 0.84	181.26 ± 10.05
CMF	1	200.00	17.12	23.74 ± 13.48	6.38	78.06	17.46 ± 4.53	8.87	25.18	129.89
CMF	2	180.00	21.47	31.92 ± 25.42	4.51	103.31	17.92 ± 7.09	6.89	26.24	169.22
CMF	3	242.00	22.81	35.57 ± 21.09	7.85	86.32	20.27 ± 4.58	10.24	25.93	146.57
CMF	4	214.00	17.80	21.98 ± 21.35	5.46	98.60	15.03 ± 6.56	7.94	26.02	141.13
Average		209.00 ± 26.05	19.80 ± 2.77	28.30 ± 6.50	6.05 ± 1.42	91.57 ± 11.51	17.67 ± 2.15	8.49 ± 1.42	25.84 ± 0.46	146.70 ± 16.54
RF26	1	296.00	9.98	21.14 ± 7.09	5.08	42.56	19.54 ± 5.32	4.40	22.10	56.25
RF26	2	324.00	11.71	21.05 ± 6.93	4.57	35.01	19.62 ± 5.51	3.74	20.67	65.57
RF26	3	362.00	15.64	21.41 ± 7.08	5.20	43.41	19.76 ± 4.81	4.56	22.23	88.26
RF26	4	362.00	11.39	17.90 ± 7.05	6.16	43.97	17.02 ± 5.26	5.86	23.31	76.91
Average		336.00 ± 27.82	12.18 ± 2.10	20.38 ± 1.44	5.25 ± 0.57	41.24 ± 3.63	18.99 ± 1.14	4.64 ± 0.77	22.08 ± 0.94	71.75 ± 13.88
RF19	1	418.00	3.79	10.34 ± 5.78	4.66	38.86	10.11 ± 4.83	4.36	21.24	19.14
RF19	2	497.00	5.49	10.27 ± 4.08	5.02	27.14	10.27 ± 3.59	4.79	20.89	24.62
RF19	3	477.00	4.85	10.24 ± 5.66	4.52	42.87	10.05 ± 4.36	4.20	24.17	26.29
RF19	4	428.00	4.75	10.17 ± 5.52	4.56	41.51	10.01 ± 4.25	4.25	23.35	25.72
Average		455.00 ± 38.06	4.72 ± 0.70	10.26 ± 0.07	4.69 ± 0.23	37.60 ± 7.17	10.11 ± 0.11	4.40 ± 0.27	22.41 ± 1.60	23.94 ± 3.28
RF14	1	626.00	7.77	13.63 ± 7.02	4.78	34.80	12.15 ± 5.25	4.53	21.52	34.11
RF14	2	548.00	7.90	12.38 ± 5.04	4.62	28.70	16.27 ± 4.29	4.29	19.28	44.51
RF14	3	524.00	9.38	11.82 ± 4.82	4.51	32.20	15.92 ± 4.22	4.22	22.03	53.00
RF14	4	558.00	7.63	12.28 ± 4.98	5.21	25.56	16.20 ± 5.20	5.20	20.26	42.43
Average		564.00 ± 43.73	8.17 ± 0.81	12.53 ± 0.77	4.78 ± 0.31	30.32 ± 4.04	15.14 ± 2.00	4.56 ± 0.45	20.77 ± 1.24	43.51 ± 7.76

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Appendix 3 Density, basal area, height and aboveground biomass of study sites (continued).

Land use type	Plot	Density (stem ha^{-1})	Basal area (m^2 ha^{-1})	Average DBH (cm)	DBH (Min.) (cm)	DBH (Max.) (cm)	Average height (m)	Height (Min.) (m)	Height (Max.) (m)	Aboveground biomass Mg ha^{-1}
RF10	1	702.00	8.86	13.01 ± 11.32	4.79	84.46	12.80 ± 5.63	4.74	25.73	66.71
RF10	2	690.00	10.27	12.74 ± 7.57	4.64	45.85	13.43 ± 5.45	4.51	23.73	76.38
RF10	3	788.00	14.62	11.12 ± 4.42	4.68	42.50	12.87 ± 4.14	4.56	22.03	74.18
RF10	4	740.00	9.60	11.26 ± 5.10	5.17	39.50	12.81 ± 4.34	5.32	20.26	52.33
Average		730.00 ± 44.15	10.84 ± 2.59	12.03 ± 0.98	4.82 ± 0.24	53.08 ± 21.08	12.98 ± 0.30	4.78 ± 0.37	22.94 ± 2.34	67.40 ± 10.87
RF9	1	761.00	3.86	8.71 ± 3.59	4.87	23.43	8.88 ± 3.04	4.90	15.64	16.49
RF9	2	811.00	5.65	8.40 ± 2.97	4.54	25.47	8.68 ± 2.61	4.50	16.33	22.84
RF9	3	766.00	4.98	8.69 ± 3.43	4.98	31.52	8.90 ± 2.90	5.04	16.93	20.99
RF9	4	710.00	6.22	9.38 ± 2.37	4.56	16.66	9.75 ± 2.27	4.53	14.50	25.85
Average		762.00 ± 41.32	5.18 ± 1.01	8.80 ± 0.41	4.74 ± 0.22	24.27 ± 6.13	9.05 ± 0.48	4.74 ± 0.27	15.85 ± 1.04	21.54 ± 3.92
FL	1	288.00	2.68	9.71 ± 11.80	4.50	95.06	8.66 ± 5.68	4.17	22.08	13.67
FL	2	304.00	2.10	6.29 ± 2.69	4.54	22.07	6.44 ± 2.66	4.39	15.98	11.45
FL	3	276.00	1.43	6.22 ± 4.60	4.50	42.09	6.12 ± 2.93	4.34	16.52	7.28
FL	4	284.00	1.73	6.22 ± 2.74	4.55	26.30	6.37 ± 2.44	4.40	14.75	9.31
Average		288.00 ± 11.78	1.99 ± 0.54	7.11 ± 1.73	4.52 ± 0.03	46.38 ± 33.58	6.90 ± 1.18	4.33 ± 0.11	17.33 ± 3.25	10.43 ± 2.75

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

Appendix 4 Composition and structural comparison of other managed forests in Thailand

Forest type	Management	Diversity (family) ≥ 4.5 cm	Density (stem ha^{-1}) ≥ 4.5 cm	Basal area (m^2 ha^{-1}) ≥ 4.5 cm	Source
Mixed deciduous	Protected watershed site	25	805.75	25.85	This study
Mixed deciduous	Community	21	209.00	19.80	This study
Deciduous	Community	23	1,290.00*	9.60*	Kabir and Webb, 2006
Dry dipterocarp	Community (Cultural forest)	25	-	-	Gomontean, 2004
Seasonal dry-evergreen	Protected environmental research station		1115.00-1,499.00	28.90-29.80	Bunyavejchewin *et al.*, 2001
Mixed deciduous	Protected watershed research station	-	171.00*	17.20*	Marod *et al.*, 1999
Deciduous	Protected forest watershed research station Disturbed forest watershed research station	- -	204.00* 254.00*	17.17* 1.76*	Yarwudhi *et al.*, 1996

* tree ≥ 5 cm in DBH

Appendix 5 Aboveground biomass and carbon in forests

Type	Location	Aboveground biomass (Mg ha^{-1})	Aboveground Carbon* (Mg C ha^{-1})	Source
Hill evergreen forest	Pa Nam Yao and Pa Nam Suad National Reserves forest, Nan	289.60	144.80	This study
Hill evergreen forest	Kaeng Krachan National Park, Petchburi	257.98	128.99	Jampanin (2004)
Dry evergreen forest	Pa Nam Yao and Pa Nam Suad National Reserves forest, Nan	268.32	134.16	This study
Dry evergreen forest (recovering forest)	Kaeng Krachan National Park, Petchburi	70.79	35.40	Jampanin (2004)
Dry evergreen forest	Thong Pha Phum National forest, Kanchanaburi	140.58	70.29	Terakunpisut and gajaseni (2003)
Dry evergreen forest (recovering forest)	Khao Ang Rue Nai Wildlife Sanctuary, Chachoengsao	199.89	99.94	Thanee (1997)
Dry evergreen forest	Khao Ang Rue Nai Wildlife Sanctuary, Chachoengsao	197.53	98.76	Thanee (1997)
Dry evergreen forest	Sakaerat Environment Research Station, Nakon Ratchasima	394.04	197.02	Sangtongpraow and Sukwong (1990);
Dry evergreen forest	Huay Hin Dard Watershed Research Station, Rayong	107.52	53.76	Suksawang (1989)
Dry evergreen forest	Sakaerat Environment Research Station, Nakon Ratchasima	302.30	151.15	Chinsukjaiprasert (1984)
Dry evergreen forest	Nam Prom Watershed, Chaiyaphum	267.57	133.78	Taweepong (1981)
Dry evergreen forest	Thailand	252.00	126.00	Drew *et al*. (1978) cited in Gajaseni, 2000
Dry evergreen forest	Thailand	126.00	60.30	Ogawa *et al*. (1965)
Mixed deciduous forest	Pa Nam Yao and Pa Nam Suad National Reserves forest, Nan	150.96	75.48	This study
Mixed deciduous forest	Queen Sirikit Botanic Garden, Chiang Mai	166.42	83.21	Rangmorya (2005)
Mixed deciduous Forest	Kaeng Krachan National Park, Petchburi	186.24	93.12	Jampanin (2004)
Mixed deciduous forest	Thong Pha Phum National forest, Kanchanaburi	96.28	48.14	Terakunpisut and gajaseni (2003)

Appendix 5 Aboveground biomass and carbon in Thailand forest (continued)

Type	Location	Aboveground biomass (Mg ha^{-1})	Aboveground carbon (Mg C ha^{-1})	Source
Mixed deciduous Forest	Thailand	31.96-175.56	15.98-87.78	Viriyabuncha *et al*. (2001)
Mixed deciduous Forest	Phu Phan Royal Development Study Center, Sakon Nakhon	140.70-197.78	70.35-98.89	Pongboon, 2000
Mixed deciduous Forest	Thailand	311.00	155.50	Ogawa *et al*. (1965)
Various forest	Malaysia	100.00-160.00	50.00-80.00	Abu-Aker, 2000 cited in Lasco, 2002
Various forest	Philippins	86.00-201.00	43.00-100.50	Lasco *et al*., 1999 cited in Lasco, 2002
Various forest	Indonesia	161.00-300.00	80.50-150.00	Murdiyarso and Wasrin, 1995 cited in Lasco, 2002

* Aboveground carbon calculated by 50% of aboveground biomass

Appendix 6 Aboveground biomass and carbon in Thailand reforestation

Site	Age (year)	Planting space (m x m)	Aboveground biomass (Mg ha^{-1})	Aboveground carbon (Mg C ha^{-1})	Source
Tectona Grandis Linn.					
Num Hean Watershed Management Unit, Nan	14	2x8	43.51	21.75	This study
Tong Pha Phum, Kanchanaburi	6	4x4	13.18	6.59	Viriyabuncha *et al*.(2004)
Tong Pha Phum, Kanchanaburi	6	4x4	17.52	8.76	Sumuntakul and Viriyabuncha (2007)
Tong Pha Phum, Kanchanaburi	11-12	4x4	60.00-109.02	30.00-54.51	Viriyabuncha *et al*. (2001)
Ngao, Lampang	14	4x4	81.78	40.89	Petmark (1977)
Tong Pha Phum, Kanchanaburi	14	4x4	120.52	60.26	Sumuntakul and Viriyabuncha (2007)
Phare	15-16	4x4	88.56-91.78	44.28-45.89	Viriyabuncha *et al*. (2001)
Mae Chang, Lampang	17	2x4	71.10	35.55	Hiratsuka *et al*. (2005)
Tong Pha Phum, Kanchanaburi	18-19	4x4	69.68-120.02	34.84-60.01	Viriyabuncha *et al*. (2001)
Chiang Mai	18-19	4x4	53.22	26.61	Viriyabuncha *et al*. (2001)
Mae Chang, Lampang	22	4x4	82.40	41.20	Hiratsuka *et al*. (2005)
Tung Kwian, Lampang	27	4x4	135.12	67.56	Viriyabuncha *et al*. (2003)
Tong Pha Phum, Kanchanaburi	27	4x4	165.98	82.99	Sumuntakul and Viriyabuncha (2007)
Eucalyptus Camaldulensis Dehnh.					
Num Hean Watershed Management Unit, Nan	19	4x4	23.94	11.97	This study
Somdet Reforestation, Kalasin	4	2x8	19.19	9.59	Jamroenprucksa (1987)
Seeding Nursery Center, Rachaburi	5	1x2	109.36	54.68	Boonyavechachevin (1990)
Lad Kra Ting, Chachoengsao	5	3x3	46.92	23.46	Viriyabuncha *et al*. (2004)
Klong Ta Krao, Chachoengsao	6	3x3	50.00	25.00	Sumuntakul and Viriyabuncha (2007)
Somdet Reforestation, Kalasin	7	2x8	54.56	27.28	Jamroenprucksa (1987)
Klong Ta Krao, Chachoengsao	14	3x3	117.12	58.56	Sumuntakul and Viriyabuncha (2007)
Gmelina arborea (Roxb.)					
Num Hean Watershed Management Unit, Nan	26	4x4	71.75	35.87	This study
Pak-Chong, Nakhonratchasima	8	2x2	85.20	42.60	Pridee (1979)
Pak-Chong, Nakhonratchasima	10	2x2	120.18	60.09	Sritulanont et al. (2004)

Appendix 7 Density of trees in different land-use types (stem ha^{-1}).

Land-use type	Sapling	Seedling
HEF	2,815.00 ± 123.99 a	25,493.00 ± 1046.10 a
DEF	2,399.00 ± 168.42 b	21,998.00 ± 1224.20 b
MDF	1,806.00 ± 19.76 c	19,875.00 ± 1270.92 c
CSF	1,704.00 ± 107.38 c	19,875.00 ± 661.72 c
CMF	1,089.00 ± 118.31 d	19,673.00 ± 764.01 e
RF26	1,052.00 ± 148.13 e	12,984.00 ± 971.13 d
RF19	1,101.00 ± 159.64 de	10,512.00 ± 703.78 e
RF14	1,241.00 ± 102.00 d	11,575.00 ± 1144.17 e
RF10	1,092.00 ± 100.88 de	11,285.00 ± 1,283.86 e
RF9	1,217.00 ± 78.07 de	11,876.00 ± 912.29 de
FL	133.00 ± 54.78 f	565.00 ± 148.93 f

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

Appendix 8 Tree families in the forest

Families	HEF	DEF	MDF	CSF	CMF
Anacardiceae	√	√	√	√	√
Annonaceae	√	√			√
Apocynaceae	√	√			
Araliaceae					√
Aquifoliaceae				√	
Araliaceae		√			
Bignoniaceae	√		√	√	√
Bombaceae			√		
Burseraceae	√	√	√	√	
Caesalpilionoideae	√	√	√		
Capparaceae		√		√	√
Celastraceae		√			
Combretaceae			√	√	
Cryteroniaceae		√	√	√	
Datiscaceae		√			
Dilleniaceae	√			√	
Dipterocarpaceae	√	√	√		
Ebenaceae			√	√	
Euphorbiaceae	√	√	√	√	√
Fagaceae	√	√		√	√
Flacourticeae	√		√	√	√
Guttiferae	√	√	√	√	√
Icacinaceae	√	√			
Irvingiaceae	√		√		
Juglandaceae	√				
Labiatae		√	√	√	√
Lauraceae	√			√	
Lythraceae	√	√	√	√	√
Magnoliaceae	√				
Malvaceae	√		√		√
Meliaceae	√	√	√	√	
Mimosoideae	√	√	√		√
Moraceae	√	√	√	√	√
Myrtaceae	√		√	√	

Appendix 8 Tree families in the forest (continued)

Families	HEF	DEF	MDF	CSF	CMF
Myristaceae	√	√		√	√
Papilionoideae	√	√	√	√	√
Rhizophoraceae			√	√	√
Rosaceae			√		√
Rubiaceae		√	√		
Sapindaceae	√	√	√	√	√
Sapotaceae	√				
Simaroubaceae			√	√	√
Sonneratiaceae		√			
Sterculiaceae	√		√		
Symplocaceae			√		√
Theacea	√				
Tiliaceae	√	√			
Verbenaceae	√			√	
Total	31	26	28	25	21

HEF = Hill evergreen forest, DEF = Dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest

Appendix 9 Tree families in the reforestation and the 6-year-old fallow land

Families	RF26	RF19	RF14	RF10	RF9	FL
Alangiaceae		√		√	√	
Anacardiceae	√	√	√	√	√	
Annonaceae	√			√		
Apocynaceae				√		
Aquifoliaceae			√			
Bignoniaceae	√	√	√	√	√	√
Burseraceae		√	√	√	√	√
Caesalpilionoideae		√		√	√	√
Celastraceae				√		
Combretaceae				√		
Cryteroniaceae		√		√	√	
Dilleniaceae	√				√	
Dipterocarpaceae		√			√	
Ebenceae	√		√	√		
Elaeocapaceae					√	
Euphorbiaceae	√	√	√	√	√	√
Guttiferae		√		√	√	√
Irvigiaceae	√			√	√	√
Labiatae	√	√	√	√	√	√
Lauraceae		√		√	√	√
Lythraceae				√		
Magnoliaceae					√	
Malvaceae				√		
Meliaceae				√		
Mimosoideae		√	√			
Moraceae		√		√	√	
Myristicaceae		√		√	√	
Myrtaceae		√				
Papilionoideae	√	√	√		√	
Rhizophoraceae		√	√	√	√	
Rubiaceae		√	√	√	√	
Sapindaceae		√		√	√	
Simaroubaceae		√		√	√	√
Staphyleaceae					√	

Appendix 9 Tree families in the reforestation (continued)

Families	RF26	RF19	RF14	RF10	RF9	FL
Symplocaceae		√	√		√	√
Total	9	21	12	25	24	10

RF26 = The 26-year-old reforestation, RF19 = The 19-year-old reforestation, RF14 = The 14-year-old reforestation, RF10 = The 10-year-old reforestation, RF9 = The 9-year-old reforestation and FL = The 6-year-old fallow land

Appendix 10 Litter biomass and carbon in forests

Forest type	Location	Litter mass ($Mg\ ha^{-1}$)	Litter carbon ($Mg\ C\ ha^{-1}$)	Source
Hill evergreen	Pa Nam Yao and Pa Nam Suad National Reserves forest, Nan	8.07	3.69	This study
Hill evergreen	Kaeng Krachan National Park, Petchburi	10.16	5.08 *	Jampanin, 2004
Hill evergreen	Doi Pui, Chiang Mai	3.09	1.54 *	Prachaiyo, 1976
Hill evergreen forest	Doi-puy, Chiangmai	6.88	3.44 *	Boonyawat and Ngampongsai (1974)**
Tropical evergreen forest	Khaochong, Trang	23.22	11.61 *	Kira *et al*. (1967)**
Dry evergreen	Pa Nam Yao and Pa Nam Suad National Reserves forest, Nan	9.51	4.20	This study
Dry evergreen	Kaeng Krachan National Park, Petchburi	10.38	5.19 *	Jampanin, 2004
Dry evergreen	Khao Ang Rue Nai Wildlife Sanctuary, Chachoengsao	6.50	3.25 *	Thanee, 1997
Dry evergreen	Huay Hin Dard Watershed Research Station, Rayong	6.86	3.43 *	Suksawang, 1989
Dry evergreen	Sakaerat Environment Research Station, Nakon Ratchasima	8.67	4.33 *	Chinsukjaiprasert, 1984
Dry evergreen forest	Namprom, Chaiyapum	7.62	3.81 *	Prachaiyo *et al*. (1980)
Dry evergreen (recovering forest)	Khao Ang Rue Nai Wildlife Sanctuary, Chachoengsao	5.86	2.93 *	Thanee, 1997
Mixed deciduous	Pa Nam Yao and Pa Nam Suad National Reserves forest, Nan	4.72	2.16	This study
Mixed deciduous	Queen Sirikit Botanic garden, Chiang Mai	8.68	2.54 *	Rangmorya (2005)
Mixed deciduous	Kaeng Krachan National Park, Petchburi	3.52	1.76 *	Jampanin, 2004
Mixed deciduous	Ngao, Lampang	7.92	3.96 *	Thaiusa et al. (1978)**
Thyrsosthachys siamensis forest	Hinlub, Kanchanaburi	4.81	2.40 *	Thaiusa *et al*. (1978)**
Primary forest	Porce region, Colombia	6.00	3.00 *	Sierra *et al*., 2007
Secondary forest	Porce region, Colombia	4.90	2.45 *	Sierra *et al*., 2007

*carbon content was estimated by 50% of mass

** cited in Visaratana and Chernkhuntod (2005)

Appendix 11 Soil properties in different land-use types

Site	Depth (Cm)	pH 1:1 H_2O	Bulk density ($g\ m^{-3}$)	OM (%)	N (%)	Avail.P (ppm)	K (ppm)	Sand (%)	Silt (%)	Clay (%)	Texture
HEF	0-20	4.03±0.03h	1.12±0.01f	4.17±0.06e	0.21±0.01e	4.65±0.32def	109.16±5.72a	53.66±2.6 ab	21.70±2.57bcde	24.64±1.31e	Sandy clay loam
	20-40	4.15±0.04j	1.34±0.01de	3.09±0.05c	0.16±0.01b	2.92±0.45b	86.53±4.69b	41.88±2.0 bcd	26.25±1.86bcde	31.87±2.85de	Clay loam
	40-60	4.24±0.06f	1.62±0.02d	2.15±0.05c	0.11±0.01c	2.35±0.31ab	76.44±4.76a	39.39±2.71c	27.93±2.06bcde	32.68±3.69d	Clay loam
	60-80	4.41±0.04g	1.80±0.02e	1.03±0.07d	0.05±0.01c	1.78±0.32b	70.25±4.26a	34.89±2.9 bc	21.16±1.50cd	43.95±3.00d	Clay
	80-100	4.52±0.04g	1.93±0.02d	0.78±0.03b	0.04±0.00b	1.14±0.32abc	60.01±4.98a	32.66±0.93c	24.61±2.70abcdef	42.73±2.28de	Clay
DEF	0-20	4.13±0.03fg	1.12±0.01f	5.02±0.09c	0.25±0.01b	4.38±0.36f	106.93±7.06a	61.72±3.87a	27.16±2.76bcde	11.12±1.14f	Sandy loam
	20-40	4.19±0.04hi	1.35±0.01d	3.47±0.04b	0.18±0.01a	2.70±0.48bc	86.53±5.27b	58.26±3.46a	28.24±2.32bcd	13.50±1.80f	Sandy loam
	40-60	4.34±0.04e	1.62±0.03d	2.48±0.05a	0.13±0.01a	2.25±0.29abc	76.42±5.39a	50.16±1.24ab	28.73±0.45bcd	21.14±1.09e	Sandy clay loam
	60-80	4.62±0.05e	1.79±0.03e	1.26±0.02bc	0.06±0.01b	1.73±0.38a	68.58±5.28a	42.26±2.85bc	30.26±1.73a	27.48±2.26e	Clay loam
	80-100	4.71±0.03e	1.93±0.02d	0.96±0.03a	0.05±0.00a	1.28±0.19ab	60.42±5.14a	36.42±2.39bc	31.74±1.65ab	31.84±2.45def	Clay loam
MDF	0-20	4.25±0.04cd	1.14±0.01e	5.15±0.09b	0.27±0.01a	4.70±0.50de	114.08±6.59a	35.35±3.27de	20.30±1.89ef	44.35±1.82bc	Clay
	20-40	4.39±0.05e	1.29±0.02g	3.57±0.05e	0.19±0.01a	2.82±0.52b	93.33±5.66a	38.31±3.03cd	30.97±0.91bc	30.72±2.16de	Clay loam
	40-60	4.48±0.05d	1.41±0.02g	2.53±0.33a	0.13±0.01a	2.19±0.28abc	80.92±4.94a	41.06±2.24c	27.99±1.73bcde	30.95±2.04d	Clay loam
	60-80	4.77±0.04d	1.50±0.02ij	1.36±0.05a	0.07±0.01a	1.79±0.38ab	73.14±4.03a	47.97±2.01ab	22.34±2.63cd	29.69±0.82e	Sandy clay loam
	80-100	4.93±0.03bc	1.60±0.02h	1.00±0.03d	0.05±0.00a	1.16±0.24ab	64.16±5.41a	54.27±1.57a	17.02±0.75e	28.71±1.65f	Sandy clay loam

Appendix 11 Soil properties in different land-use types (Continued)

Site	Depth (Cm)	pH 1:1 H_2O	Bulk density (g m^{-3})	OM (%)	N (%)	Avail.P (ppm)	K (ppm)	Sand (%)	Silt (%)	Clay (%)	Texture
CSF	0-20	4.22±0.03de	1.14±0.02e	3.50±0.07gh	0.18±0.01d	4.34±0.57f	86.87±5.29b	29.70±2.91ef	31.84±1.94ab	38.46±2.19cd	Clay loam
	20-40	4.29±0.03f	1.32±0.03e	2.72±0.05e	0.14±0.01cd	2.64±0.38bc	63.45±4.43d	22.13±1.71ef	31.74±1.14ab	46.13±2.24ab	Clay
	40-60	4.33±0.04e	1.48±0.04e	2.19±0.49c	0.11±0.01c	2.06±0.34bdc	49.36±5.10cd	18.95±1.59g	30.70±1.13ab	50.35±1.59abc	Clay
	60-80	4.4.40±0.04gh	1.57±0.04gh	1.25±0.04bc	0.06±0.00b	1.54±0.31bc	32.28±4.15cd	16.45±1.45g	30.38±1.50a	53.17±1.04ab	Clay
	80-100	4.52±0.03g	1.75±0.04f	0.69±0.04c	0.03±0.01c	0.92±0.22bcd	25.67±3.34cd	15.59±1.08f	29.74±1.25ab	54.67±0.95abcd	Clay
CMF	0-20	4.07±0.05g	1.18±0.02d	3.56±0.07fg	0.22±0.01cd	3.74±0.34gh	93.21±6.58b	25.49±2.26fg	24.32±3.82bcde	50.19±1.64ab	Clay
	20-40	4.20±0.04ghi	1.31±0.02fg	2.90±0.07d	0.15±0.01bc	2.33±0.54bcd	65.70±4.41d	25.06±3.65ef	23.33±4.34def	51.61±0.78a	Clay
	40-60	4.32±0.03e	1.49±0.03e	2.40±0.05b	0.12±0.01b	1.89±0.40cdef	53.27±4.53ef	21.80±3.32fg	22.72±3.83bcde	55.48±3.36a	Clay
	60-80	4.36±0.03hi	1.62±0.02f	1.22±0.04c	0.06±0.00b	1.30±0.24bc	37.99±3.99b	19.29±1.65fg	21.92±3.26cd	58.79±2.75a	Clay
	80-100	4.51±0.03g	1.78±0.03ef	0.71±0.02c	0.04±0.01bc	0.88±0.29bcd	34.04±2.99b	19.50±1.17ef	18.99±0.99def	61.51±1.75ab	Clay
RF26	0-20	4.17±0.05ef	1.13±0.02ef	4.41±0.23d	0.18±0.01e	5.02±0.56cde	60.05±4.40e	42.38±1.69cd	19.95±1.17ef	37.67±1.63d	Clay loam
	20-40	4.23±0.02g	1.26±0.03g	2.37±0.05g	0.13±0.01d	2.84±0.58b	42.20±4.27fg	33.51±2.54de	20.66±0.90ef	45.83±2.48abc	Clay
	40-60	4.29±0.04ef	1.35±0.02i	1.68±0.08ef	0.09±0.01d	1.96±0.43bcde	36.27±4.53ef	28.61±2.09ef	23.33±2.92bcde	48.06±2.75bc	Clay
	60-80	4.33±0.03i	1.50±0.03i	1.33±0.10ab	0.07±0.01ab	1.51±0.46bc	28.87±4.69def	25.59±0.83ef	22.91±3.26cd	51.50±1.77bc	Clay
	80-100	4.42±0.03h	1.67±0.04g	0.50±0.04f	0.03±0.00d	0.95±0.35bcd	23.32±3.13def	24.18±2.50de	23.02±3.06abcdef	52.80±0.73bcd	Clay

Appendix 11 Soil properties in different land-use types (Continued)

Site	Depth (Cm)	pH 1:1 H_2O	Bulk density (g m^{-3})	OM (%)	N (%)	Avail.P (ppm)	K (ppm)	Sand	Silt (%)	Clay	Texture
RF19	0-20	4.10±0.05g	1.12±0.02ef	3.48±0.09gh	0.18±0.01d	4.42±0.47ef	57.84±3.86e	29.89±1.38ef	27.95±1.34bcd	42.16±1.71d	Clay
	20-40	4.13±0.04j	1.33±0.04def	2.08±0.07h	0.11±0.01e	2.42±0.42bcd	41.25±3.34fg	27.80±2.00ef	25.92±1.45bcdef	46.28±1.80ab	Clay
	40-60	4.20±0.02i	1.41±0.03fg	1.77±0.05d	0.09±0.01d	2.16±0.31bc	32.68±2.93f	22.11±1.06fg	28.22±1.36bcd	49.67±0.79abc	Clay
	60-80	4.33±0.03i	1.53±0.03hi	1.28±0.08bc	0.07±0.01ab	1.55±0.36bc	26.67±1.55f	20.10±0.98fg	29.46±0.92ab	50.44±0.56bcd	Clay
	80-100	4.50±0.03g	1.73±0.05f	0.52±0.06ef	0.03±0.00d	0.98±0.34bcd	20.15±2.22f	18.01±1.69ef	30.23±1.03a	51.76±0.75cd	Clay
RF14	0-20	4.20±0.02d	1.09±0.01g	5.46±0.08a	0.28±0.02a	6.29±0.97b	108.25±3.73a	47.90±1.24bc	21.72±1.49bcde	30.38±0.89e	Sandy clay loam
	20-40	4.37±0.03e	1.31±0.04efg	2.10±0.08h	0.12±0.01e	2.99±0.69b	71.33±2.72c	37.09±2.36cd	23.86±1.65cdef	39.05±0.89bc	Clay loam
	40-60	4.43±0.03d	1.44±0.03f	1.55±0.15f	0.08±0.01d	1.91±0.44bcdef	56.50±4.40b	29.67±2.66de	23.57±2.71bcde	46.76±0.85c	Clay
	60-80	4.57±0.04f	1.57±0.03g	0.96±0.08d	0.05±0.01c	1.19±0.42cd	37.78±2.93b	25.08±3.05ef	21.84±1.60cd	53.08±2.59abc	Clay
	80-100	4.90±0.03cd	1.67±0.03g	0.60±0.07d	0.03±0.00cd	0.80±0.34cd	31.11±5.31bc	22.22±0.87de	19.44±0.31cde	58.34±0.87a	Clay
RF10	0-20	4.07±0.04gh	1.09±0.02g	3.70±0.16f	0.19±0.01cd	4.20±0.46fg	65.24±3.99d	20.71±2.57g	29.26±2.03bc	50.03±1.48ab	Clay
	20-40	4.09±0.12i	1.28±0.02g	2.33±0.13g	0.13±0.01d	2.11±0.28cd	41.46±3.62f	20.70±2.42f	27.79±1.48bcde	51.51±1.01a	Clay
	40-60	4.12±0.03j	1.39±0.03gh	1.76±0.08de	0.09±0.01d	1.73±0.25def	35.97±2.66ef	19.23±1.37g	27.32±1.61bcde	53.45±0.78abc	Clay
	60-80	4.13±0.04j	1.52±0.04ij	1.42±0.11a	0.07±0.01a	1.31±0.29bcd	28.40±4.04cdef	18.97±1.39fg	25.66±1.07abc	55.37±1.25ab	Clay
	80-100	4.26±0.03i	1.65±0.03g	0.59±0.06de	0.03±0.00cd	0.83±0.23cd	21.41±1.68ef	17.74±0.88ef	23.78±0.91c	58.48±1.59abc	Clay

Appendix 11 Soil properties in different land-use types (Continued)

Site	Depth (Cm)	pH 1:1 H_2O	Bulk density ($g\ m^{-3}$)	OM (%)	N (%)	Avail.P (ppm)	K (ppm)	Sand	Silt (%)	Clay	Texture
RF9	0-20	4.25±0.04cd	1.08±0.03g	3.45±0.08h	0.18±0.01d	3.68±0.28hi	55.92±3.44e	46.15±1.50bc	16.68±1.67f	37.17±1.73d	Sandy clay
	20-40	4.32±0.07ef	1.20±0.03h	2.56±0.09f	0.12±0.01d	1.88±0.28cd	38.09±2.82g	39.07±1.34cd	18.78±2.21f	42.15±1.51bc	Clay
	40-60	4.47±0.05d	1.36±0.03hi	1.79±0.17de	0.09±0.01d	1.29±0.19g	33.04±2.46f	29.75±2.11de	21.52±1.49de	48.73±0.78abc	Clay
	60-80	4.61±0.06ef	1.49±0.03j	1.37±0.04a	0.07±0.01a	0.83±0.17d	27.16±2.74ef	24.29±1.81ef	23.41±1.36bcd	52.30±0.62abc	Clay
	80-100	4.65±0.05f	1.67±0.03g	0.49±0.03f	0.03±0.00d	0.52±0.18de	20.37±2.14e	21.73±1.12de	24.56±0.99bc	53.71±0.74bcd	Clay
AG1	0-20	4.31±0.04c	1.16±0.01d	4.09±0.18e	0.21±0.01e	2.40±0.43i	59.69±4.60e	28.14±1.69efg	21.10±1.27de	50.76±1.65a	Clay
	20-40	4.46±0.04d	1.28±0.02g	2.29±0.12g	0.12±0.01d	1.56±0.31ae	44.03±3.09f	26.93±1.30ef	20.13±0.77ef	52.94±1.23a	Clay
	40-60	4.63±0.27c	1.40±0.01g	0.69±0.09ij	0.04±0.01f	1.18±0.24g	35.52±2.82ef	26.49±0.71def	18.62±0.50e	54.89±0.71ab	Clay
	60-80	4.81±0.04cd	1.59±0.01g	0.39±0.07fg	0.02±0.01de	0.84±0.28d	30.86±2.36cd	25.89±2.25ef	17.53±0.73d	56.58±1.67ab	Clay
	80-100	4.96±0.04b	1.80±0.01e	0.26±0.04gh	0.01±0.01fg	0.40±0.19e	21.08±2.41ef	25.40±2.14d	16.06±0.40f	58.54±1.80abc	Clay
AG2	0-20	4.13±0.04fg	1.32±0.01c	2.40±0.06j	0.14±0.01fg	3.23±0.80h	56.86±4.50e	38.89±1.26cd	24.74±1.81bcde	36.37±1.67d	Clay loam
	20-40	4.15±0.04ij	1.44±0.01c	1.87±0.03i	0.11±0.01e	2.10±0.54cd	43.76±3.65f	38.85±4.04cd	25.35±2.82bcdef	35.80±1.77cd	Clay loam
	40-60	4.25±0.07f	1.72±0.01c	0.85±0.04g	0.05±0.01e	1.59±0.49defg	36.75±3.15e	36.57±2.56cd	27.86±2.17bcde	35.57±2.17d	Clay loam
	60-80	4.31±0.02h	1.88±0.03d	0.48±0.02e	0.03±0.00d	1.17±0.49cd	30.97±2.91cd	35.77±1.44cd	30.57±1.71a	33.66±1.93e	Clay loam
	80-100	4.42±0.04h	1.98±0.02c	0.23±0.04h	0.01±0.01fg	0.74±0.30d	23.55±2.25de	35.92±2.30bc	32.73±1.41a	31.35±1.34ef	Clay loam

Appendix 11 Soil properties in different land-use types (Continued)

Site	Depth (Cm)	pH 1:1 H_2O	Bulk density (g m^{-3})	OM (%)	N (%)	Avail.P (ppm)	K (ppm)	Sand	Silt (%)	Clay	Texture
AG3	0-20	5.05±0.05a	1.52±0.01a	2.56±0.06i	0.15±0.01f	8.34±0.80a	67.72±4.16d	20.11±1.54g	30.01±1.80ab	49.88±2.85ab	Clay
	20-40	5.12±0.05a	1.67±0.01a	1.39±0.03j	0.09±0.01f	5.70±1.23d	53.66±2.63e	20.79±0.90f	31.01±2.18bc	48.20±2.47ab	Clay
	40-60	5.18±0.04a	1.87±0.02a	0.73±0.13hi	0.04±0.00f	2.90±0.74a	37.28±3.11e	21.95±1.29fg	30.41±2.16bcde	47.64±2.59bc	Clay
	60-80	5.20±0.07a	2.01±0.03a	0.44±0.03f	0.03±0.00f	2.16±0.29a	30.54±3.79cde	22.85±1.61fg	30.69±2.12a	46.46±1.61cd	Clay
	80-100	5.34±0.06a	2.10±0.01a	0.28±0.03g	0.02±0.00ef	1.52±0.38a	22.64±2.82de	23.91±1.82de	32.31±1.50a	43.78±0.34ef	Clay
AG4	0-20	4.54±0.04b	1.43±0.01b	2.14±0.08l	0.12±0.01g	3.34±0.80h	67.64±3.52cd	49.57±1.99bc	24.80±1.95bcde	25.63±0.69e	Sandy clay loam
	20-40	4.70±0.04b	1.56±0.01c	0.89±0.07l	0.05±0.01h	2.07±0.23d	54.39±3.54e	43.63±0.93bc	26.34±1.84bcde	30.03±0.57d	Clay loam
	40-60	4.73±0.07b	1.81±0.02b	0.66±0.04j	0.04±0.00f	1.55±0.38ef	45.06±4.98d	40.70±0.28c	28.26±0.82bcd	31.04±0.77d	Clay loam
	60-80	4.84±0.03c	1.97±0.03b	0.34±0.02g	0.02±0.01e	1.11±0.34cd	36.68±2.55b	37.66±1.28cd	29.88±0.83abc	32.46±2.10e	Clay loam
	80-100	4.86±0.06d	2.06±0.03b	0.17±0.01i	0.01±0.00g	0.65±0.29de	32.61±2.90b	33.68±1.33c	31.31±1.77abc	35.01±1.99ef	Clay loam
AG5	0-20	4.48±0.03b	1.45±0.01b	2.22±0.05k	0.13±0.01g	3.49±0.80h	71.57±4.32c	52.67±2.50b	19.98±2.12ef	27.35±0.87e	Sandy clay loam
	20-40	4.59±0.04c	1.63±0.02b	1.07±0.02k	0.06±0.01g	2.00±0.34d	56.09±3.49e	48.56±1.69b	20.87±1.32ef	30.57±0.67d	Sandy clay loam
	40-60	4.66±0.04c	1.78±0.03b	0.68±0.06ij	0.04±0.00f	1.51±0.16f	44.42±3.26d	43.57±1.15bc	24.65±0.87cd	31.77±0.54d	Clay loam
	60-80	4.91±0.05b	1.94±0.02c	0.26±0.03h	0.02±0.00e	1.19±0.32cd	36.84±1.92b	42.09±0.96bc	24.58±1.21abc	33.33±0.73e	Clay loam
	80-100	5.00±0.07b	2.07±0.02b	0.17±0.01i	0.01±0.00g	0.67±0.25d	32.60±1.69b	39.35±0.31b	25.23±0.23abcd	35.42±0.43f	Clay loam

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old).

Appendix 12 Carbon and nitrogen ratio in soil

Land use type	0-20 cm	20-40 cm	40-60 cm	60-80 cm	80-100 cm
HEF	11.18 ± 0.66 abc	11.48 ± 0.49 a	11.33 ± 0.48 ab	11.31 ± 0.64 ab	11.39 ± 0.44 ab
DEF	11.71 ± 0.65 ab	11.48 ± 0.54 a	11.40 ± 0.45 ab	11.29 ± 0.44 ab	11.11 ± 0.49 abcd
MDF	11.09 ± 0.48 b	11.16 ± 0.56 a	11.35 ± 0.45 ab	10.81 ± 0.94 ab	10.93 ± 0.72 abcde
CSF	11.55 ± 0.72 ab	11.38 ± 0.51 a	11.43 ± 0.44 ab	11.50 ± 0.67 a	11.54 ± 0.43 a
CMF	11.40 ± 0.78 ab	11.51 ± 0.64 a	11.57 ± 0.39 a	11.49 ± 0.41 a	11.28 ± 0.46 abc
RF26	11.66 ± 0.33 a	10.86 ± 0.83 ab	10.90 ± 0.52 b	10.98 ± 0.94 ab	10.20 ± 1.17 cdefg
RF19	11.39 ± 0.33 ab	11.25 ± 0.49 a	11.32 ± 0.32 ab	11.15 ± 0.63 ab	10.92 ± 0.44 bcde
RF14	11.49 ± 0.79 ab	11.27 ± 0.61 a	11.15 ± 0.44 ab	10.76 ± 0.49 b	10.76 ± 0.35 de
RF10	11.12 ± 0.73 abc	11.21 ± 0.60 ab	10.92 ± 0.64 ab	11.01 ± 0.76 ab	10.47 ± 0.36 ef
RF9	11.15 ± 0.47 b	11.18 ± 0.73 ab	11.18 ± 0.55 ab	11.14 ± 0.60 ab	10.77 ± 0.54 cde
FL	11.47 ± 0.39 ab	10.86 ± 0.88 ab	10.87 ± 0.53 b	9.55 ± 0.24 c	10.87 ± 0.37 cde
Litchi	10.08 ± 1.20 cd	9.97 ± 1.29 bc	9.43 ± 0.75 c	9.37 ± 0.97 c	9.72 ± 0.85 fg
Rice	10.06 ± 0.70 d	9.46 ± 0.74 c	9.78 ± 0.62 c	9.36 ± 0.58 c	9.82 ± 0.70 fg
Corn1	9.94 ± 0.46 d	9.46 ± 0.53 c	9.46 ± 0.71 c	9.27 ± 0.94 c	9.98 ± 0.58 f
Corn2	9.74 ± 0.47 d	9.60 ± 0.61 c	9.50 ± 0.76 c	9.33 ± 0.57 c	9.05 ± 0.67 g

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old).

Appendix 13 Soil carbon (at 1 m depth) in Thailand forest

Type	Location	Soil C (Mg C ha^{-1})	Source
Hill evergreen forest	Pa Nam Yao and Pa Nam Suad National Reserves forest, Nan	221.94	This study
Hill evergreen forest	Doi Sutep-Pui National Park, Chiangmai	127.20-305.95	Janmahasatien and Phopinit (2001)
Dry evergreen forest	Pa Nam Yao and Pa Nam Suad National Reserves forest, Nan	214.29	This study
Dry evergreen forest	Erawan National Park, Kanchanaburi	200.00	Janmahasatien and Phopinit (2001)
Dry evergreen forest	Doi Sutep-Pui National Park, Chiangmai	90.50	Janmahasatien and Phopinit (2001)
Dry evergreen forest	Sakaerat Environment Research Station, Nakon Ratchasima	231.05	Janmahasatien *et al.* (2004)
Mixed deciduous forest	Pa Nam Yao and Pa Nam Suad National Reserves forest, Nan	181.76	This study
Mixed deciduous forest (conservation forest)	Pa Nam Yao and Pa Nam Suad National Reserves forest, Nan	163.91	This study
Mixed deciduous forest (community forest)	Pa Nam Yao and Pa Nam Suad National Reserves forest, Nan	171.54	This study
Mixed deciduous Forest	Mae Klong watershed, Research station, Kanchanaburi	195.42	Janmahasatien *et al.* (2004)
Mixed deciduous forest (secondary growth)	Mae Klong watershed, Research station, Kanchanaburi	154.90-168.40	Janmahasatien and Phopinit (2001)
Mixed deciduous forest (old growth)	Erawan National Park, Kanchanaburi	108.63-287.79	Janmahasatien and Phopinit (2001)
Mixed deciduous Forest	Doi Sutep-Pui National Park, Chiangmai	108.00	Janmahasatien and Phopinit (2001)

Appendix 14 Carbon pools ratios in different land-use types

Land use type	Aboveground vegetation carbon	Litter carbon	Coarse woody debris	Fine root carbon	Coarse root carbon	Soil organic carbon
HEF1	1.00	0.02	0.02	0.03	0.10	1.48
HEF2	1.00	0.03	0.03	0.03	0.09	1.54
MDF	1.00	0.03	0.02	0.05	0.14	2.18
CSF	1.00	0.02	0.02	0.04	0.11	1.72
CMF	1.00	0.03	0.02	0.05	0.14	2.18
P1979	1.00	0.04	0.02	0.09	0.18	3.73
P1986	1.00	0.06	0.03	0.21	0.39	8.91
P1991	1.00	0.10	0.03	0.14	0.29	6.24
P1995	1.00	0.05	0.02	0.10	0.20	4.01
P1996	1.00	0.05	0.03	0.18	0.43	9.84
FL	1.00	0.02	0.01	0.08	0.09	19.14
Litchi	1.00	0.00	0.00	0.07	0.06	12.37
Rice	1.00	0.00	0.00	0.19	0.00	42.00
Corn1	1.00	0.00	0.00	0.20	0.00	16.09
Corn2	1.00	0.00	0.00	0.20	0.00	16.51

Where, HEF = Hill evergreen forest, DEF = dry evergreen forest, MDF = Mixed deciduous forest, CSF = Conservation forest, CMF = Community forest, RF26 = Reforestation which planted in 1979 (26-year-old), RF19 = Reforestation which planted in 1986 (19-year-old), RF14 = Reforestation which planted in 1991 (14-year-old), RF10 = Reforestation which planted in 1995 (10-year-old), RF9 = Reforestation which planted in 1996 (9-year-old), FL = Fallow land (6-year-old)

APPENDIX B

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RESEARCH PAPER

Profiles of carbon stocks in forest, reforestation and agricultural land, Northern Thailand

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Abstract: A study was conducted to assess carbon stocks in various forms and land-use types and reliably estimate the impact of land use on C stocks in the Nam Yao sub-watershed (19°05′10″N, 100°37′02″E), Thailand. The carbon stocks of aboveground, soil organic and fine root within primary forest, reforestation and agricultural land were estimated through field data collection. Results revealed that the amount of total carbon stock of forests (357.62 ± 28.51 Mg·ha^{-1}, simplified expression of Mg (carbon)·ha^{-1}) was significantly greater ($P< 0.05$) than the reforestation (195.25 ± 14.38 Mg·ha^{-1}) and the agricultural land (103.10 ± 18.24 Mg·ha^{-1}). Soil organic carbon in the forests (196.24 ± 22.81 Mg·ha^{-1}) was also significantly greater ($P< 0.05$) than the reforestation (146.83 ± 7.22 Mg·ha^{-1}) and the agricultural land (95.09 ± 14.18 Mg·ha^{-1}). The differences in carbon stocks across land-use types are the primary consequence of variations in the vegetation biomass and the soil organic matter. Fine root carbon was a small fraction of carbon stocks in all land-use types. Most of the soil organic carbon and fine root carbon content was found in the upper 40-cm layer and decreased with soil depth. The aboveground carbon:soil organic carbon: fine root carbon ratios (ABGC: SOC: FRC), was 5:8:1, 2:8:1, and 3:50:1 for the forest, reforestation and agricultural land, respectively. These results indicate that a relatively large proportion of the C loss is due to forest conversion to agricultural land. However, the C can be effectively recaptured through reforestation where high levels of C are stored in biomass as carbon sinks, facilitating carbon dioxide mitigation.

Keywords*:* carbon stock; aboveground carbon; soil organic carbon; fine root carbon; land use; Thailand

Introduction

It is clear that fossil fuel emissions dominate the anthropogenic perturbation of the global carbon cycle. Land use changes currently drive the largest proportion of anthropogenic emissions in a number of tropical regions of Asia (Canadel 2002). According to the Kyoto Protocol, land use, land-use change, and forestry (LULUCF) are recognized as serving the role of carbon source and sink in relation to a change in land cover and carbon stocks. It also influences the amount of biomass and carbon stored in vegetation (IPCC 2000). Land-use changes also affects soil carbon (C) storage because soils are either carbon sources or sinks depending upon the variable response of soil C pools to land-cover change (Power et al. 2004). Forests are the most important carbon pool on land. Approximately 60%–70% of carbon in forests is stored as organic material in the soil (Janssens et al. 1999). Accordingly, the conversion of forests to agricultural land not only reduces C stocks in vegetation but also causes significant losses of soil organic carbon (Post and Kwon 2000). Reduction of soil C stocks are also associated with agricultural management *i.e.* residue removal *via* harvesting or burning, and soil tillage (Hairiah et al. 2001).

A number of recent studies on the association of carbon storage with land-use shifts have focused on *in situ* carbon change in tropical zones. Lasco (2002) found that deforested areas covered with grasses and annual crops, have carbon densities that are typically less than 40 Mg·ha^{-1} (simplified expression of Mg (carbon)·ha^{-1}). This is much less than the carbon densities found in natural forests. The conversion of natural forests to tree plantations and perennial crops reduce carbon density by at least 50% when compared to natural forests (Lasco 2002). In the lower Mekong basin, paddy fields and grassland have aboveground carbon less than 4% of that in primary dipterocarp forest (Gajaseni 2000).

In Thailand, forest degradation has been identified as a major contributing factor to carbon stock losses. FAO (2003) estimated that Thailand's annual forest loss was at 112 million hectares per year, during the period 1990–2000 (0.7% annually). Over the period 2000-2004, Thailand lost an average of 60 475 ha of natural forest per year (National Park, Wildlife and Plant Conservation Department 2005). The deforestation rate has declined slightly since the period 1990–1995 due to already diminished forest

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cover as well as increasing public and governmental ecological interest (FAO 2003). Estimates of Thailand's CO_2 emissions in 1994 were 241 Tg, and the projected level of CO_2 emissions in 2020 were approximately 583 Tg to 777 Tg. Total CO_2 emissions would continue to increase because of a more than two fold increase in energy consumption between the years 2000 and 2020. The average increase of CO_2 emission from the energy and forestry sectors is about 5% annually (OEPP 2000).

Based on current information, reforestation is believed to have the potential to contribute to C storage directly through accumulation of C in biomass and soil (Richter et al. 1999; Silver et al. 2000). Facilitating reforestation by establishing plantations on abandoned and degraded agricultural land in the tropics has been proposed as an effective carbon management approach (Montagnini and Porras 1998). According to FAO (2001), forest plantations account for 187 million hectares in Asia which is the largest amount in any region globally. Reforestation in Thailand often consists of a mix of planted and naturally regenerated species. Both native and exotic species are grown in reforestation areas. In particular, exotic, fast-growing species are often chosen for reforestation when native species are difficult to establish. The presence of planted community is likely to affect carbon dynamics. However, reforestation and forest plantation in Thailand seem to be more concerned with improvement of degraded forest ecosystems than carbon management and climate change mitigation. Despite the abundance of estimates of forest biomass in Thailand, the data is not capable of facilitating direct comparisons across various land use types. Lack of distinctions between forest, reforestation and agricultural land and incomplete measurements of carbon pools in each land use make comprehensive analysis difficult. This lack of information hinders any attempt to optimally utilize the findings in the studies. On this basis, the understanding of carbon stocks in land use is essential to addressing Thailand climate change mitigation efforts.

In order to reliably estimate the impact of land use on C stocks, this study included the estimates of C storage in various forms including aboveground, fine root and soil C within forests, reforestations and agricultural lands in Nam Yao sub-watershed. This area is also known as the main catchment of Nan watershed, which covers an area of 34 331 km^2 in Thailand. The objectives of this study are: (i) to assess carbon stock in various forms in different land-use types; and (ii) to estimate the relative amounts of carbon stocks between aboveground and belowground for use in climate change mitigation.

Methods

Study site

The study area is located in Nam Hean watershed management unit area, Num Yao sub-watershed, Nan province (19°05′10″N, 100°37′02″E). The land area is approximately 19 000 ha (Fig. 1). The elevation ranges from 215 to 1 674 m a.s.l. The soil parent material consists of sandstone, shale stone and lime stone. Soils are mainly Red Yellow Podzolic soils and Reddish Brown Lateritic soils. The average air temperature is 16.9°C during the dry season and 32.5°C during the wet season. Average annual precipitation is 1 405 mm. The land cover types consist of hill evergreen and mixed deciduous forest, reforestation, orchard, cornfields, paddy fields, and small part of other crop cultivations. In this area, the natural forest has been severely degraded during the past thirty years due to legal and illegal logging, shifting agriculture, and uncontrolled forest fires. Because of the severe deterioration of the forest conditions, reforestation initiatives have become a high priority to the Royal Thai Government. Since the 1960s, reforestation activities have been implemented in the degraded areas of Nam Hean watershed. Farmland and heavily eroded areas were replanted with fruit and economic trees by hill tribes and Thais. In the late 1970s, plans to reforest depleted areas by planting native and exotic species for the purpose of watershed conservation were designed and implemented (Royal Forest Department 1998).

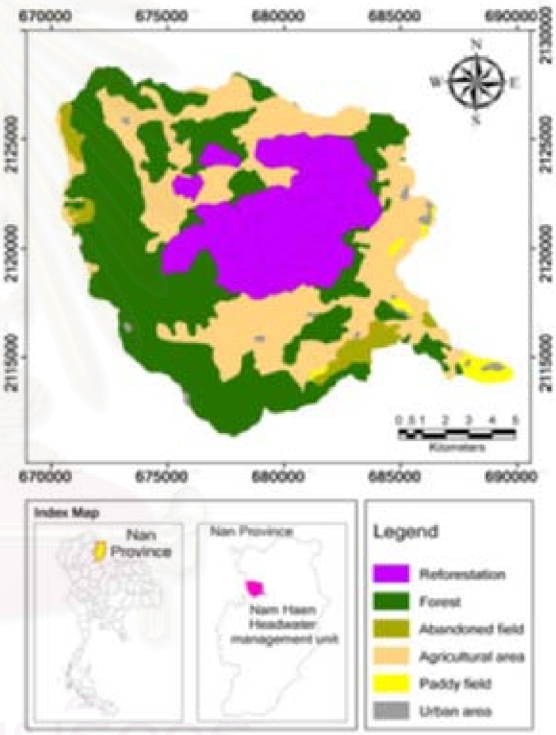

Fig. 1 Location of the study area

The study was conducted in three main land-use types: forest, reforestation, and agricultural land. All five natural forest sites had been protected from logging for over half a century, three of which were hill evergreen forest, and two were mixed deciduous forests (Table 1). The reforested sites were planted with four native species and two exotic species in 1979 (Table 1). The agricultural sites were cleared prior to 1957 after which these areas were privately owned and cultivation of small grain and corn was practiced by illegal private owners. The agricultural sites included fallow land (6-year fallow), orchard (*Litchi chinensis* Sonn. spp.), paddy fields, and corn fields which still employ conventional tillage and chemical fertilizers (Table 1).

Table 1. Sample collection: location and ownership of forest sites, reforestation sites and agricultural sites within Num Haen Watershed Management unit

Sites		Location	Type/plantation	Plot size (m^2)	Ownership
Forest	F1	47Q 0672289 UTM 2125707	Hill evergreen forest	50 x 50	National Park Reserves
	F2	47Q 0672583 UTM 2124503	Hill evergreen forest	50 x 50	National Park Reserves
	F3	47Q 0671989 UTM 2126546	Hill evergreen forest	50 x 50	National Park Reserves
	F4	47Q 0680732 UTM 2115809	Mixed deciduous forest	50 x 50	National Park Reserves
	F5	47Q 0685006 UTM 2116909	Mixed deciduous forest	50 x 50	National Park Reserves
Reforestation	RF1	47Q 0684082 UTM 2122527	*Gmelina aborea* Roxb. (exotic)	50 x 50	Num Haen Watershed Management Unit
	RF2	47Q 0680748 UTM 2119676	*Eucalyptus camaldulensis* Dehn. (exotic) *Tectona grandis* Linn. (native)	50 x 50	Num Haen Watershed Management Unit
	RF3	47Q 0683003 UTM 2122381	*Tectona grandis* Linn. (native)	50 x 50	Num Haen Watershed Management Unit
	RF4	47Q 0679903 UTM 2119368	*Tectona grandis* Linn. (native) *Pterocarpus macrocarpus* Kurz. (native) *Afzelia xylocarpa* (Kurz) Craib. (native)	50 x 50	Num Haen Watershed Management Unit
	RF5	47Q 0680990 UTM 2119752	*Tectona grandis* Linn. (native) *Pterocarpus macrocarpus* Kurz. (native) *Afzelia xylocarpa* (Kurz) Craib. (native) *Acacia catechu* (L.f.) Willd (native)	50 x 50	Num Haen Watershed Management Unit
Agriculture	A1	47Q 0683820 UTM 2123305	Fallow land (6-year fallow)	50 x 50	Private landowner
	A2	47Q 0673679 UTM 2126388	Orchard (*Litchi chinensis* Sonn. spp.)	50 x 50	Private landowner
	A3	47Q 0681248 UTM 2117440	Paddy field (*Oryza sativa* Linn.)	1 x 1	Private landowner
	A4	47Q 0673788 UTM 2126210	Corn field (*Zea mays* L.)	1 x 1	Private landowner
	A5	47Q 0681215 UTM 2124023	Corn field (*Zea mays* L.)	1 x 1	Private landowner

Note: location codes refer to Fig. 1

Data collection

Aboveground carbon and carbon stocks

To assess the biomass, plots of 50 m × 50 m were established in all land-use types. The number of plots chosen for each land-use type was based on its distribution in the study area and the expected variability in the amount of carbon. In the forest, the most common type of hill evergreen and mixed deciduous areas were expected to have a high degree of variability in the amount of carbon thus a larger number of plots ($n = 32$) were selected. Reforested areas, were expected to have lower variability in the amount of carbon, and fewer plots ($n = 20$) were chosen. For agricultural land, the selected plots were located in various fields ($n = 28$). In fallow land and orchards, selected plots of 50 m × 50 m were established ($n = 8$). Corn fields and paddy fields were selected with the plots size of 1 m × 1 m ($n = 20$) regarding the homogenous pattern and limited damage to the farmers. All individual trees of ≥ 4.5 cm diameter at breast height (dbh) at 1.30 m height above the ground were measured and identified. Trees were divided into two size classes of dbh: small tree (≤ 25 cm) and large tree (> 25 cm). Density ($\text{individual}\cdot\text{ha}^{-1}$), basal area ($\text{m}^2\cdot\text{ha}^{-1}$) and biomass ($\text{Mg}\cdot\text{ha}^{-1}$) were calculated. The aboveground biomass was calculated using the developed allometric equations in Thailand for hill evergreen forest (Tsutsumi et al. 1983), mixed deciduous forest (Ogawa et al. 1965), *Gmelina aborea* Roxb. (Sritulanont et al. 1983) *Eucalyptus camaldulensis* Dehn. (Kamo 1999), *Tectona grandis* Linn. (Viriyabuncha et al. 2001), and Bamboo (*Thyrsostchys siamensis*, Suwannapinunt 1983; *Gigantchloa albociliata* and *Bambusa tulda*, Kutintara et al. 1995). We developed the following equations for *Litchi chinensis* Sonn. spp. tree at the site as follows:

$$\text{Log}\ Ws = 0.8712 \log D^2H - 1.5735 \qquad r^2 = 0.9941$$

$$\text{Log}\ Wb = 0.8023 \log D^2H - 1.7695 \qquad r^2 = 0.9858$$

$$\text{Log}\ Wl = 1.2113 \log D^2H - 2.5229 \qquad r^2 = 0.9823$$

Where D is the diameter at breast height (cm) and H the height (m); Ws the stem dry weight, Wb the branch dry weight, and Wl is the leave dry weight; $n = 10$.

The biomass of the understory layer consisting of < 4.5 cm diameter trees (saplings) were analyzed in the 25 sub plots of 4 m × 4 m in each plot of 50 m × 50 m. Seeding and herbs were analyzed in the 25 sub plots of 1m × 1 m in each sapling plot in forest, reforestation, fallow land, and orchards. Mean wet weight was obtained from each species by measuring wet weight of individuals. Sub samples were oven-dried to determine the ratio of dry-wet weight. The ratios were then applied over the entire sample of each species for conversion to dry weight. All aboveground components were assumed to have 50% C content (Brown and Lugo 1984; Levine et al. 1995).

Fine root carbon and soil carbon stocks

The soil samples were collected consisting of five random samples in each 50 m × 50 m plot across land-use types. The number of soil samples in forest, reforestation and agricultural land was 160, 100 and 115, respectively. The soil was sampled by soil cores, hereafter referred to as soil profiles, to a depth of 100 cm and separated into layers 0–20, 20–40, 40–60, 60–80, and 80–100 cm. In order to detect the soil organic carbon (SOC) storage change without destroying soil structure, soils bulk density was measured by using a cutting ring. Root size ≤5 mm in diameter was separated by hand sorting and then successively sieved through 5 mm and 2 mm mesh sieve to remove the remaining root fragments from each layer. Roots were weighed fresh and then oven-dried at

90°C for 12 h to constant weight. Wet-dry weight ratio was determined for each sample. Organic carbon contents in root and soil were determined based on three replicates using the Walkley-Black method (Walkley and Black 1934). This method oxidizes only the organic carbon while avoiding interference by carbonates (Hesse 1971). The SOC content of each layer was calculated for bulk density and summed for the entire soil profile to estimate total SOC content. The distribution of fine root carbon (FRC) in each profile was calculated from the soil confined to a depth of 100 cm.

Soil properties

Soil was passed through a 2-mm mesh sieve and air-dried approximately for 48 h. Soil texture was analyzed by the hydrometer method after dispersion with sodium hexametaphosphate (Sheldrick and Wang 1993). Soil pH was measured by a glass electrode in the supernatant of a 1:1 soil/water suspension. Bulk densities were measured by volume and weight (Blake and Hartge 1986). Soil nitrogen was analyzed by the Kjeldahl Method. The mean amount of SOC for any specific soil depth was calculated as the average for all soil profiles of each layer.

Results and discussion

Aboveground biomass and aboveground carbon (ABGC)

According to the results of the study, variances in biomass of ≥ 4.5 cm dbh. individual trees between the forest and the reforestation were large (Table 2). Trees compose a large proportion of basal area and biomass, with significant differences observed between the forest and the reforestation. Although the reforestation areas have more trees than in the forest, most trees are ≤ 25 cm in dbh representing highest biomass density. In the forest, the most aboveground biomass accumulation was found in trees > 25 cm dbh. The total basal area decreased from 32.62 ± 10.27 $m^2 \cdot ha^{-1}$ in the forest to 8.51 ± 1.08 $m^2 \cdot ha^{-1}$ in the reforestation. However, the proportion of trees ≤ 25 cm dbh increased and dominated in terms of basal area and biomass in the reforestation. Trees ≤ 25 cm dbh accounted for 8.96% of total biomass in the forest while 50.47% of that in the reforestation. On the other hand, the trees > 25 cm dbh accounted 89.49% and 29.36% of the total biomass in the forest and the reforestation, respectively (Table 2).

Table 2. Density, basal area, biomass and total aboveground carbon in different land-use type.

Class	Forest			Reforestation			Agriculture
	Density (stem·ha^{-1})	Basal area ($m^2 \cdot ha^{-1}$)	Biomass (Mg·ha^{-1})	Density (stem·ha^{-1})	Basal area ($m^2 \cdot ha^{-1}$)	Biomass (Mg·ha^{-1})	Biomass (Mg·ha^{-1})
Understory	-	-	4.23a ± 0.65	-	-	12.07b ± 1.38	-
Dbh ≤ 25 cm	200.85a ± 24.36	4.55a ± 0.74	24.34a ± 5.15	432.25b ± 45.27	6.00b ± 1.03	30.20b ± 4.83	-
Dbh > 25 cm	133.05a ± 12.25	28.07a ± 3.50	243.17a ± 36.42	85.60b ± 9.14	2.51b ± 1.58	17.57b ± 3.16	-
Total	333.90a ± 19.66	32.62a ± 10.27	271.74a ± 45.15	517.85b ± 43.31	8.51b ± 1.08	59.84b ± 8.21	12.20c ± 1.66

Mean followed by the different letters (a, b and c) within the same row indicate significant differences ($P < 0.05$).

With increasing forest age and development, the biomass of understory layer (saplings, seeding and herbs) declined and became a very small proportion of the total biomass (Table 2). The biomass of understory layer in the reforestation was significantly greater than that in the forest. The understory biomass of the forest accounted for only 1.56% of total aboveground biomass. Comparison of total aboveground biomass in different land-use types indicated that the total aboveground biomass in forest was significantly higher than that in the reforestation and the agricultural land ($P < 0.05$). The amounts of total aboveground carbon storage in the forest, reforestation and agricultural land were estimated at 135.87 ± 22.57 Mg·ha^{-1}, 29.92 ± 4.10 Mg·ha^{-1} and 6.10 ± 0.83 Mg·ha^{-1} (simplified expression of Mg (carbon)·ha^{-1}), respectively. Therefore, the levels of aboveground biomass are directly reflected the variability of carbon stock in different land-use types.

C stocks in biomass of the reforestation and the agricultural land account for only 22.02% and 4.49% of the original content in natural forest (Table 2). This proportion was found to be lower than other secondary forests when compared to original content (32%, Jampanin and Gajaseni 2004; 29%, Viriyabuncha et al. 2002; and 28%, Bonino et al. 2006). It can be compared to the proportion found in the shrubby grassland (5%) in the Chancaní reserve in Mexico (Bonino et al. 2006). We concluded that the natural forest possesses a high potential for aboveground carbon storage. Unfortunately, it is easily degraded or lost by land-use change. Therefore, it is essential to establish forest protection and conservation policies due to the long period required to accumulate carbon through reforestation. Lands with degraded vegetation cover are identified as having potential for restoration (Iverson et al. 1993), because it contains a lower carbon biomass density than the maximum potential value for the site and type of vegetation. Greater development of the understory and small trees (dbh ≤ 25 cm) in reforestation is a very important component of aboveground biomass. Furthermore, these main groups will have great potential for sequestration in the future if the area is managed appropriately.

The aboveground carbon storage of forest (135.87 ± 22.57 Mg·ha^{-1}) falls to the range of other forests in Thailand (63.00 Mg·ha^{-1}, Ogawa et al. 1965; 197.02 Mg·ha^{-1}, Sangtongpraow and Sukwong 1990; 98.76 Mg·ha^{-1}, Tanee 1997; and 70.29 Mg·ha^{-1}, Teerakunpisut 2003). Compared to studies in neighboring countries, our results were fairly similar to the natural forests in Malaysia (100.00–160.00 Mg·ha^{-1}, Abu-Aker 2000 cited in Lasco 2002), Philippines (86.00–201.00 Mg·ha^{-1}, Lasco et al. 1999 cited in Lasco 2002) and Indonesia (161.00–300.00 Mg·ha^{-1}, Murdiyarso and Wasrin 1995 cited in Lasco 2002). These results suggest that a large proportion of the net accumulation of above-ground biomass in tropical forests occurs as continued growth of large trees as opposed to ingrowths of smaller individuals (Lugo and Brown 1992). While reforestation demonstrated relatively low carbon storage within the range for mixed deciduous in Thailand (15.97–87.75 Mg·ha^{-1}, Viriyabuncha et al. 2002). It must be noted that the carbon storage of reforestation in this study was lower than findings in other studies (165.50 Mg·ha^{-1}, Ogawa et al. 1965; 48.14 Mg·ha^{-1}, Teerakunpisut 2003; and 93.12 Mg·ha^{-1}, Jampanin and Gajaseni 2004).

Soil properties

All soils in the study were strongly acidic regardless of land-use types. Average pH ranged from 4.38 ± 0.56 to 4.91 ± 0.28 and increased with soil depth (Table 3). Soil pH was significantly higher in the agricultural land than that in the forest and the reforestation, whereas no significant difference ($P < 0.05$) was observed between the forest and reforestation.

Table 3. Mean and standard deviation of soil characteristics and soil organic carbon in 0-100 cm soil depth in different land-use type.

Land use	Soil depth (cm)	pH	Bulk density (g·cm^{-3})	% clay	C:N ratio	Soil organic C (Mg·ha^{-1})	Total soil organic C (Mg·ha^{-1})
Forest	0-20	4.38a ± 0.56	1.19a ± 0.22	20.25a ± 14.62	11.42a ± 0.68	58.96a ± 8.48	196.24a ± 22.81 (100.00 %)
	20-40	4.41a ± 0.35	1.34a ± 0.22	24.75a ± 13.73	11.43a ± 0.55	50.37a ± 6.26	
	40-60	4.55a ± 0.41	1.58a ± 0.62	34.00a ± 13.56	11.34a ± 0.48	43.41a ± 4.82	
	60-80	4.61a ± 0.30	1.74a ± 0.90	36.85a ± 14.06	11.29a ± 0.62	24.58a ± 2.83	
	80-100	4.64a ± 0.22	1.89a ± 0.07	40.08a ± 15.04	11.30a ± 0.74	18.92a ± 3.24	
Reforestation	0-20	4.40a ± 0.27	1.10b ± 0.28	39.70b ± 7.33	11.36ab ± 0.59	52.51b ± 9.82	146.83b ± 7.22 (74.82 %)
	20-40	4.42a ± 0.20	1.28b ± 0.54	46.94b ± 3.87	11.16b ± 0.67	33.93b ± 2.28	
	40-60	4.56a ± 0.36	1.39b ± 0.04	52.68b ± 3.78	11.09b ± 0.52	27.55b ± 2.72	
	60-80	4.60a ± 0.33	1.52b ± 0.04	53.84b ± 3.53	11.01b ± 0.70	22.34b ± 2.97	
	80-100	4.66a ± 0.31	1.68b ± 0.05	55.60b ± 3.59	10.37b ± 1.50	10.50b ± 1.35	
Agriculture	0-20	4.55b ± 0.46	1.39c ± 0.12	36.71c ± 10.28	10.22c ± 0.88	42.08c ± 7.80	95.09c ± 14.18 (48.45 %)
	20-40	4.61b ± 0.39	1.53c ± 0.14	38.15c ± 9.29	9.83c ± 0.95	25.42c ± 6.94	
	40-60	4.70b ± 0.35	1.73c ± 0.16	39.55c ± 8.89	9.77c ± 0.93	14.22c ± 2.13	
	60-80	4.79b ± 0.37	1.89c ± 0.14	41.22c ± 8.80	9.52c ± 1.08	8.19c ± 1.90	
	80-100	4.91b ± 0.28	2.02c ± 0.11	42.80c ± 9.00	9.62c ± 0.86	5.18b ± 1.63	

Mean followed by the different letters (a, b and c) within the same column indicate significant differences ($P < 0.05$)

The average bulk density in all soil layers was significantly higher in the agricultural land than in the forest and the reforestation ($P < 0.05$). The bulk density tended to increase as the soil depth increased. This is possibly due to more organic matter in topsoil than subsoil.

The clay content of soil differed among the three land-use types. The average clay percentage was significantly higher ($P < 0.05$) in the reforestation than in the agricultural land and the forest. The soil in the forest had the lowest clay content (< 40%). The subsoil had noticeably higher clay content than the surface soil in all land-use types. In addition, the surface soil in the forest was found to be rich in sand particles and is likely due to leaching of clay particles to the subsoil by rainfall but clay content in subsoil in the forest was not greater than that in the reforestation and the agricultural land.

Changes in land use also effected carbon-nitrogen (C:N) ratios. The mean C:N ratios in all soil layers in the forest (but not in top layer) were significantly higher ($P < 0.05$) than the reforestation and the agricultural land. In each land-use type, the C:N ratios narrowly varied less than 1 throughout the soil profile.

We concluded that land use changes significantly affect soil bulk densities and the C:N ratios. These factors also induce SOC variation. Organic C content shows a negative relationship with bulk density. This relation is observed in the field when organic C content increases as bulk density decreases (Sonja et al. 2005). For instance, the conversion of grassland into cropland indicates the increase of bulk density and the decrease of SOC (Evrendilek et al. 2004). Moreover, some other soil properties (*i.e.* total porosity and C:N ratio), affect root development and are closely related to soil organic matter concentration (Prévost 2004).

Soil organic carbon (SOC) and fine root carbon (FRC)

The vertical distribution of SOC also varied among the three land-use types. The overall average proportion of SOC was higher in the forest and the reforestation than in the agricultural land. In all land-use types, the deposition of SOC was generally higher in the top soil (0–20 cm) and decreased with soil depth. The highest proportion of SOC content was deposited in the 0–20 cm depth. SOC content was found to be 30.04%, 35.76 and 44.25%, in the forest, reforestation and agricultural land respectively. The total SOC content in the forest (196.24 ± 22.81 Mg·ha^{-1}) was significantly higher than the content in the reforestation (146.83 ± 7.22 Mg·ha^{-1}) and the agricultural land (95.09 ± 14.18 Mg·ha^{-1}) (Table 3).

The vertical distribution of FRC also varied among land-use types (Table 4). At all soil depths, the average FRC in the forest was much higher than in the reforestation and the agricultural land. Regardless of land use, the deposition of FRC as soil organic matter was generally higher in the top soil and decreased with soil depth. The study also found that the highest proportion of FRC content was in the top layer of soil in the agricultural land

(70.68%), followed by the reforestation (49.08%) and the forest (42.81%). However, the plant composition in each land-use type evolves differently due to the root structure of annual and perennial plants. The total root carbon content decreased from 25.51 ± 4.01 Mg·ha^{-1} in the forest to 18.50 ± 3.53 Mg·ha^{-1} in the reforestation and 1.91 ± 0.42 Mg·ha^{-1} in the agricultural land (Table 4).

Table 4. Mean and standard deviation of fine root carbon 0–100 cm soil depth in different land-use type.

Land use	Soil depth (cm)	Root carbon (Mg·ha^{-1})	Total (Mg·ha^{-1})
Forest	0-20	10.92a ± 2.20	25.51a ± 4.01 (100.00 %)
	20-40	8.26a ± 1.09	
	40-60	4.04a ± 0.92	
	60-80	1.48a ± 0.15	
	80-100	0.81a ± 0.11	
Reforestation	0-20	9.08b ± 1.45	18.50b ± 3.53 (72.52 %)
	20-40	6.06b ± 1.03	
	40-60	2.17b ± 0.15	
	60-80	0.88b ± 0.21	
	80-100	0.31b ± 0.19	
Agriculture	0-20	1.35a ± 0.08	1.91c ± 0.42 (7.49 %)
	20-40	0.46c ± 0.03	
	40-60	0.07b ± 0.02	
	60-80	0.02b ± 0.01	
	80-100	0.01c ± 0.00	

Mean followed by the different letters (a, b and c) within the same column indicate significant differences ($P < 0.05$)

SOC pool and soil properties are heavily influenced by land use (Ussiri et al. 2006). The SOC is generally found to decrease rapidly following the conversion from a natural to agricultural ecosystem. It is clear that the conversion of forest into reforestation and agricultural land decreased SOC by 74.82% and 48.45%, respectively (Table 3). The result corresponds to the study of Mendoza-Vega (2003) where the open land (grassland and cropland) in the highlands of Mexico contained only 20%–60% of SOC observed in the forests. Rationally, soil C loss in the agricultural land is caused by cultivation along with removal of crop production and crop residues. This reduces decomposition and affects soil C deposition. Based on previous research on soil properties after deforestation in Thailand, the reduction of organic matter decomposition was found to be the major contributing factor causing decreases of total C content in the surface soil layers of crop fields (Obara et al. 2000). However, agricultural land has the potential to increase soil C sequestration if proper agricultural practices and management are implemented (Sperow et al. 2003). Soil C can be sequestered in reforestation overtime, even during the later stages of succession (Silver et al. 2004).

In terms of SOC and soil depth, the results clearly demonstrated the vertical distribution. The highest SOC was found at the surface soil (Mendoza-Vega et al. 2003, Chowdhury et al. 2007). This study indicated that more than 55% of total SOC in soil deposited in the 0–40 cm depth. In order to maintain soil productivity, special care must be taken in preserving the first 40 cm depth since less drastic changes in deeper layers have been observed (IC-SEA 2000).

Fine root carbon tends to accumulate in surface soil. Fine root located in the upper part of the soil profile appears to be influenced by the availability of nutrients in the soil (Schmid and Kazda 2002). Very few studies have estimated FRC in the tropics. In Chiapas highlands in Mexico, Mendoza-Vega et al. (2003) estimated the fine root carbon at 29.00–42.70 Mg·ha^{-1} (in the depth of 0–100 cm) in forest and 4.20 Mg·ha^{-1} in open land. Their findings were higher than the findings in this study largely due to a greater availability of aboveground and soil organic carbon in the highlands of Mexico. Moreover, differences in vegetation and soil type play an important role in the FRC pool. The fine roots may grow from C that has been stored in the tree at times and may take up C from the soil during or subsequent to initial growth (Trumbore et al. 2006).

Total carbon stock (TCS) and changes

TCS (sum of ABGC, SOC and FRC to 1 m depth) varied significantly over land-use types. The ABGC portion of TCS in the forest, reforestation and agricultural land was 37.99%, 15.32% and 5.92%, respectively. SOC accounted for a large proportion of TCS, representing 54.87% in the forest, 75.20% in the reforestation and 92.23% in the agricultural land. FRC represented 7.13% in the forest, 9.47% in the reforestation and 1.85% in the agricultural land. The TCS among the three land-use types varied significantly which decreased from 367.62 ± 28.51 Mg·ha^{-1} in the forest to 195.25 ± 14.38 Mg·ha^{-1} in the reforestation and to 103.10 ± 18.24 Mg·ha^{-1} in the agricultural land (Table 5).

Changes TCS are associated with shifts in land use and/or land management practices. The estimates of TCS varied greatly over land-use types in this study. The greatest TCS loss overall occurred in the agricultural land, with the major contribution in ABGC. ABGC in the forest is five and twenty two times higher than in the reforestation and the agricultural land, respectively. SOC in the forest is higher than the reforestation and the agricultural land by one and two times respectively. FRC in the forest is higher than the reforestation and the agricultural land by approximately one and seven times, respectively. In this study, SOC content was found to be larger than ABGC content over the land-use types. SOC showed the least drastic changes among them. The data indicated that the ABGC pool is highly responsive to land-use change while the SOC is more resistant than other pools. However, it can be concluded that the SOC accumulates more slowly than ABGC. The slow SOC turnover rates, as compared to aboveground vegetation, suggests that soil C level does not react as quickly to change in land use (see also Walker and Desanker 2004). Growing vegetations tend to maintain SOC level by continuously supplying C from root turnover when compared with bare land, which tends to deplete C (Sanchez et al. 2002). The ABGC:SOC:FRC ratios represent C fractions among pools and can be used to estimate the proportion of C stocks in different land uses in this region. The ratios indicated that the conversion of forest to agricultural land caused high C allocation shift from 5:8:1 to 3:50:1. This effect was substantial in aboveground C, while the C storage in the soil was less susceptible to depletion (Table 5).

For the area of this study (19 000 ha^{-1}), the forests, the reforestations and the agricultural land cover a large proportion of total area (20%, 23% and 47%) and the total amount of carbon stored were 1 358.96 Gg C, 853.24 Gg C and 920.68 Gg C, respectively. These results indicate that a relatively large proportion of the C loss was due to the conversion of forest to agricultural land. However, this C may be recaptured in the reforestation projects, which would be an effective C mitigation by sequestering C in above-and belowground.

Table 5. Total carbon stocks in different land-use type

Land use type	ABGC ($Mg·ha^{-1}$)	% of TCS	SOC ($Mg·ha^{-1}$)	% of TCS	FRC ($Mg·ha^{-1}$)	% of TCS	TCS ($Mg·ha^{-1}$)	% of TCS	Ratio ABGC : SOC : FRC
Forest	135.87a ± 22.57	37.99	196.24a ± 22.81	54.87	25.51a ± 4.01	7.13	357.62a ± 28.51	100.00	5:8:1
Reforestation	29.92b ± 4.10	15.32	146.83b ± 7.22	75.20	18.50b ± 3.53	9.47	195.25b ± 14.38	100.00	2:8:1
Agriculture	6.10c ± 0.83	5.92	95.09c ± 14.18	92.23	1.91c ± 0.42	1.85	103.10c ± 18.24	100.00	3:50:1

Mean followed by the different letters (a, b and c) within the same column indicate significant differences ($P < 0.05$)

Conclusion

We found a large variation of carbon pools in different land-use type in northern Thailand. The ABGC, SOC and FRC are potentially sequestered highest in the forest and decreased in the reforestation and the agricultural land significantly due to the different biomass production. These findings indicate that C loss related to land-use change in northern Thailand, which has removed the aboveground biomass, soil organic carbon and even fine root carbon from each land-use type. These ABGC:SOC:FRC ratios are highest in the forestation (5:8:1) followed by the reforestation (2:8:1) and the agricultural land (3:50:1), respectively. It means that if we convert the forest to the agricultural land, the C loss from aboveground biomass will be greater than the other carbon pools. In the SOC content, the top soil (0-20 cm) can sequester highest C which is similarly found in all land-use types. In conclusion, it confirms that the forest is playing the important role as a carbon sink in terrestrial ecosystem. Nevertheless, it is essential to understand the potentiality of C sequestration in different carbon pools (ABGC, SOC, and FRC) particularly in forest ecosystem comparing to the other land-use types which will be an substantial information for the carbon mitigation and the implementation of "Land Use, Land-Use Change and Forestry (LULUCF)" concept for carbon sink.

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